DRAFT
REMEDIAL INVESTIGATION REPORT

BERRY'S CREEK STUDY AREA
REMEDIAL INVESTIGATION

Submitted to

U.S. Environmental Protection Agency

Submitted by

Berry's Creek Study Area Cooperating PRP Group

June 2016

Report Contributors

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LIST OF ACRONYMS

^{137}Cs	cesium-137
AVS	acid volatile sulfides
AOC	administrative order on consent
BAZ	biologically active zone
BCC	Berry's Creek Canal
BCSA	Berry's Creek Study Area
BERA	baseline ecological risk assessment
BMP	baseline monitoring program
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act
COPC	chemical of potential concern
CSM	conceptual site model
CSO	combined sewer overflow
EnCap	EnCap Golf LLC
EPA	U.S. Environmental Protection Agency
FS	feasibility study
LBC	Lower Berry's Creek
MBC	Middle Berry's Creek
MERI	Meadowlands Environmental Research Institute
MSL	mean sea level
NJDEP	New Jersey Department of Environmental Protection
NJMC	New Jersey Meadowlands Commission
NJPDES	New Jersey Pollutant Discharge Elimination System
NJSEA	New Jersey Sports and Exposition Authority
NOAA	National Oceanic and Atmospheric Administration
PAH	polycyclic aromatic hydrocarbon
PCB	polychlorinated biphenyl
PIC	Peach Island Creek
POC	particulate organic carbon
POTW	publicly owned treatment works
ppm	part per million
ppt	part per thousand
QAPP	quality assurance project plan
RBSL	risk-based screening level
RI	remedial investigation
RI/FS	remedial investigation/feasibility study
SCP	Scientific Chemical Processing
SET	surface elevation table
SOW	statement of work

SPI	sediment profile imaging
SSE	selective sequential extraction
STP	sewage treatment plant
TAL	target analyte list
TSS	total suspended solids
UBC	Upper Berry's Creek
UOP	Universal Oil Products
USACE	U.S. Army Corps of Engineers
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey

Note: Tables and figures may have additional acronyms and abbreviations.

EXECUTIVE SUMMARY

Introduction

The Berry's Creek Study Area (BCSA, or the site) Cooperating Potentially Responsible Party Group (hereafter referred to as "the BCSA Group") entered into an Administrative Order on Consent (AOC) in 2008 with the U.S. Environmental Protection Agency (EPA) Region 2 to perform a remedial investigation and feasibility study (RI/FS) pursuant to the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). The scope of the RI/FS is described in a statement of work (SOW) attached as Appendix B to the AOC. As defined by the SOW, the purpose of the RI/FS is "to characterize the nature and extent of contamination as provided in this SOW and evaluate remedial alternatives that mitigate potential human health and ecological risks associated with the biouptake and environmental fate and transport of chemicals from historical and on-going sources of hazardous substance releases from various facilities, while taking into account other sources of chemical and non-chemical stressors and relevant background conditions."

More simply stated, the overall objective of the RI/FS process is to characterize the site-related hazardous substances in the tidal zone of the BCSA to allow EPA to make decisions that address risks to human health and the environment. Based on periodic briefings, EPA recently recognized that the RI findings support a multi-phase remedial approach that initially focuses on the waterways in the northern end (Upper Berry's Creek [UBC] and Middle Berry's Creek [MBC], described below) of the tidal zone (Letter from Carole Petersen, Chief, NJ Remediation Branch, to Peter Brussock, Project Coordinator for the BCSA Group, June 13, 2016). This will be the initial step in an adaptive process that will target both the areas of highest risks, and the legacy waterway sediments that are the ongoing source of chemicals of potential concern (COPCs) that drive risk and are hindering ongoing recovery throughout the BCSA. Subsequent monitoring of the system response to initial remedial action will likely reduce the uncertainty of other risk estimates and better support selection of subsequent remedial actions. EPA's adaptive management approach to the BCSA remedy was taken into account in preparing this RI report to ensure that the important supporting elements from 8 years of studies were clearly identified and adequately discussed.

Studies conducted during the RI provide a thorough, in-depth understanding of the physical, chemical, and biological conditions that exist within the BCSA, and this information collectively identifies the site characteristics and risk factors that should be taken into account in the FS.

The RI has identified primary and secondary COPCs that are evaluated in the risk assessments (see Section 1 of RI text). Mercury, methyl mercury, and polychlorinated biphenyls (PCBs) are the primary COPCs important to defining site risks and have been the focus of investigations. Other COPCs (e.g., chromium, copper, lead and nickel) also were present at the site and are evaluated in the risk assessments. The RI documents the range of COPC concentrations present and their general distribution in site media. In general, COPC concentrations are highest in the northern reaches of the system and decrease moving towards the Hackensack River. Vertically within the sediment profile, the highest COPC concentrations are typically found at depth and are well beneath the zone where most biological activity occurs.

Significant portions of the RI concentrated on understanding the hydrodynamic conditions that move the COPCs around the system, and the geochemical and biological factors that collectively limit or influence their bioavailability. The RI documented that COPC fate is tied to sediment movement within the study area and that much of the sediment load in the BCSA is derived from the Hackensack River. Studies focused on marsh-waterway interactions have demonstrated and confirmed that COPCs move into marshes from the waterways and become trapped. Over time cleaner sediments are burying elevated COPC concentrations, especially in marshes, a process that contributes to natural recovery of the ecosystem. *Phragmites australis* (*Phragmites*), the dominant plant species in the BCSA, plays an important role in marsh resilience and maintaining the stability of the marshes. Importantly, methylation and bioaccumulation of mercury appear to be occurring, but at lower rates than at other mercury sites. These site-specific factors will be important when evaluating risk and making remedy decisions.

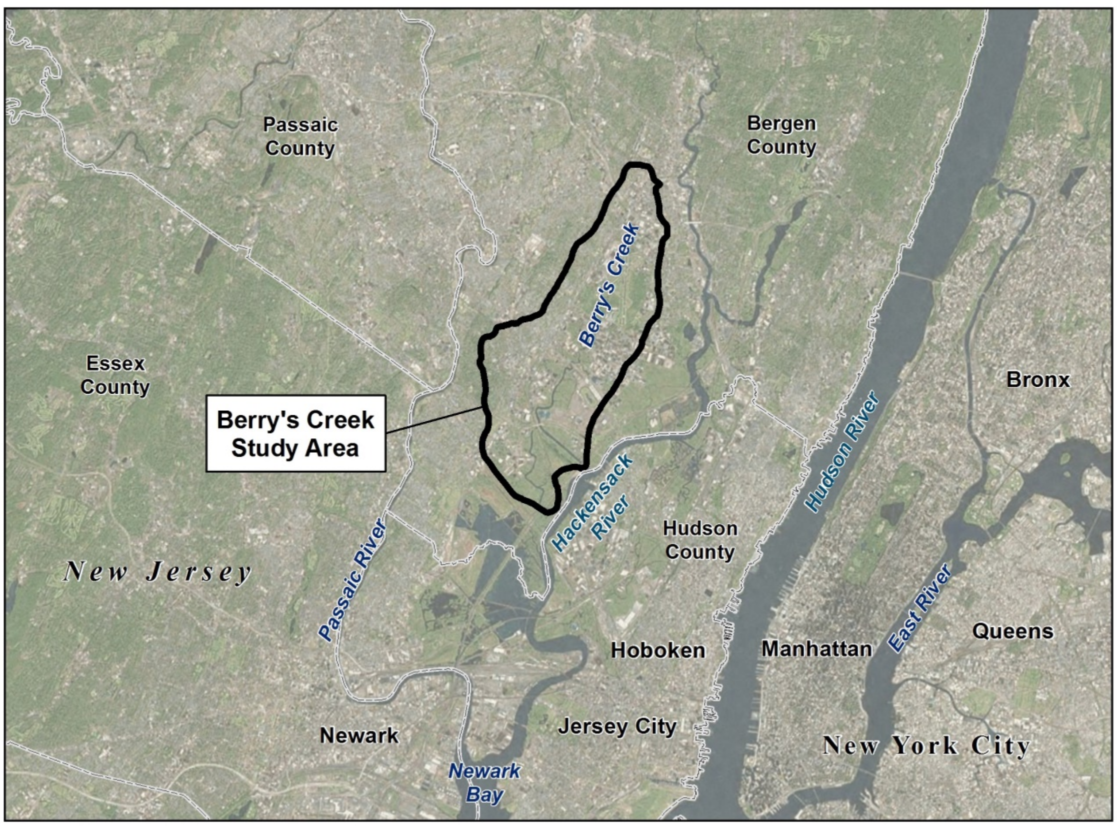
As an outcome of conducting a progression of related studies over 8 years to understand the food web and human use activities, the RI has established an in-depth understanding of the human and ecological receptors that might be at risk in the BCSA. Overall human uses are low and likely will remain so for the foreseeable future, especially in marshes. Ecological risks exist in waterways and some major tributaries, especially at mudflats. A robust data set is now available to support assessments of both human and ecological risks.

This RI Report documents the extensive information and data collected from 2008 through 2015. Some uncertainties remain even after this multi-year extensive RI investigation, such as future rates of natural recovery. Additional areas of uncertainty will be identified and discussed as part of the human health and ecological risk assessments to be submitted shortly as part of the draft RI Report. However, the adaptive management strategy EPA has directed for the BCSA provides a framework for a remedy that starts where uncertainties have been mostly resolved, and requires monitoring to address remaining ones prior to design of future actions.

Findings presented in this Executive Summary are regarded as the primary site characterization and risk factors that should be taken into account in the FS. Previous agency comments on RI/FS-related documents and the BCSA Group's responses have been addressed throughout the RI Report as cataloged in Appendix A. Supporting documentation, lines of evidence, cross-referencing of data analysis/presentation, and references to support the findings in the Executive Summary are provided throughout the text of the RI Report and appendices. Some cross-referencing to sections in the RI Report and appendices is provided in this Executive Summary for convenience to the reader.

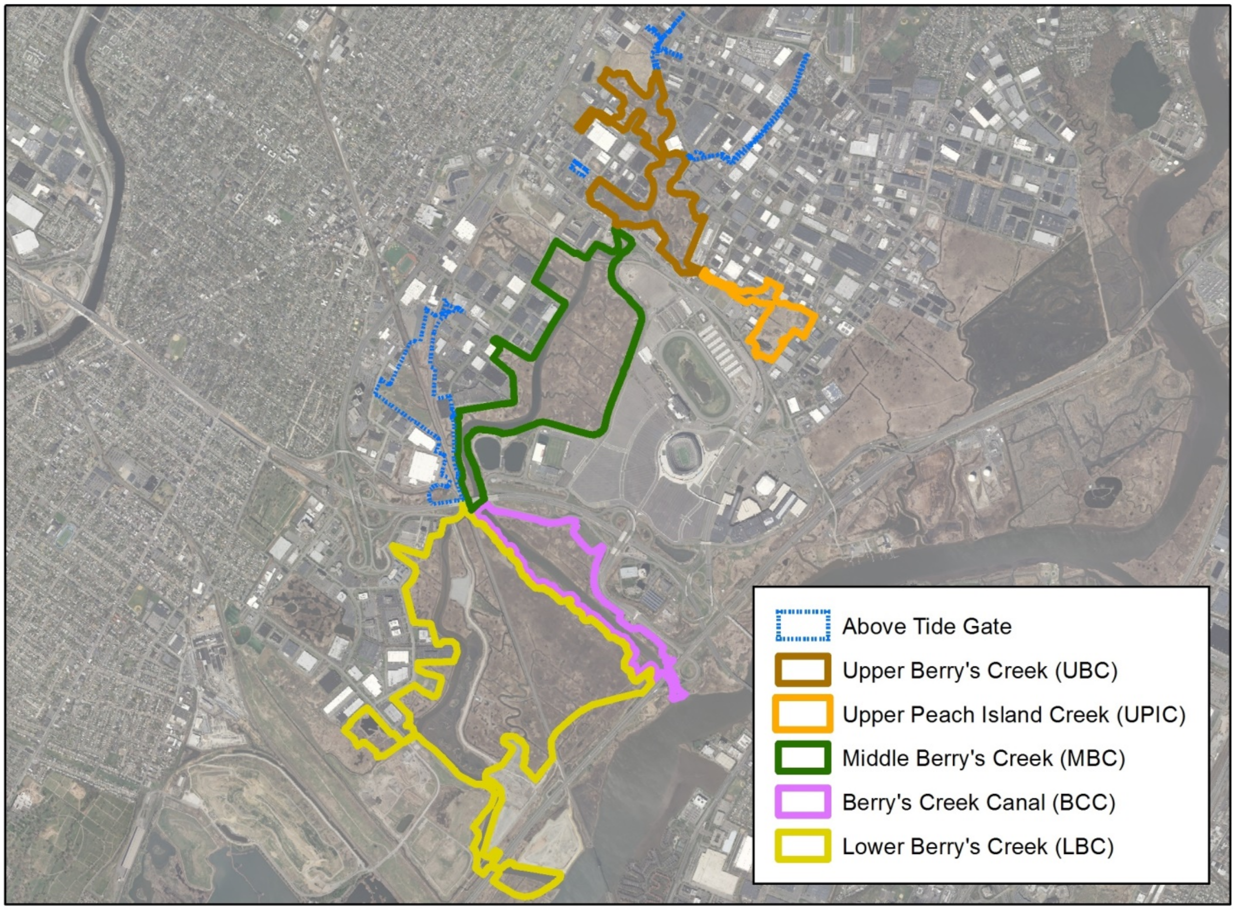
Site Setting and History (Section 4-1; Appendices B and E)

The BCSA is an urban watershed located in the Hackensack Meadowlands in Bergen County, New Jersey (Graphic ES-1) within one of the most populous and developed regions of North America. The BCSA is defined by the Berry's Creek watershed situated along the middle of the Hackensack River estuary. The watershed consists of approximately 1,029 acres (1.6 mi^2) of tidal waterways and marshes (the "tidal zone") that are the focus of the RI/FS, and 6,670 acres (10.4 mi^2) of highly-urbanized uplands areas that drain to the BCSA tidal zone. Commercial and industrial land use dominates the area directly surrounding the tidal area, while residential land use is largely limited to the uplands above the 100-year flood zone.



Graphic ES-1. Location of BCSA in Bergen County, New Jersey

Four study segments have been distinguished for reference in discussing the site and are designated: UBC, MBC, Berry's Creek Canal (BCC), and Lower Berry's Creek (LBC) (Graphic ES-2). In addition, the area in UBC above the Peach Island Creek tide gate is often referred to as Upper Peach Island Creek (UPIC). Three reference sites were also studied in the RI and were selected based on similar tidal dynamics, vegetation, geology, and salinity: Bellman's Creek and Mill Creek (tributaries to the Hackensack River north and east of the BCSA), and Woodbridge River on the south end of Arthur Kill.



Graphic ES-2. BCSA Study Segments

The BCSA tidal zone (approximately 75 percent marshes and 25 percent waterways) is a tidal fringe marsh of the Hackensack River estuary, and the physical, chemical, and biological structure of the BCSA is closely tied to the interaction of tidal flow and uplands freshwater flow within the system. Tidal water from the Hackensack River flows into and out of the BCSA twice daily—resulting in routine exchange between the estuary and the BCSA. Although tidal flow is dominant throughout the BCSA, freshwater baseflow and episodic storm runoff draining from the urban watershed interacts with tidal flows resulting in a gradient of physical and chemical conditions along the study area. The Hackensack River accounts for the majority of the sediment deposited in the tidal area of the BCSA.

The common reed (*Phragmites australis*) marshes are a dominant feature of the BCSA, occupying approximately 90 percent of the emergent vegetation habitat in the tidal zone. The physical structure of the *Phragmites* marshes creates a broadly stable landscape that provides habitat for various fauna and supports consistent sediment deposition as a result of routine flooding by tidal water. Estuarine marshes are among the most productive ecosystems in the world and organic matter derived from the *Phragmites* marshes influences overall ecosystem function as well as COPC fate and transport.

Human activities have resulted in multiple physical, chemical, and biological stressors that have impacted the BCSA and surrounding area. These stressors, when combined with a network of interrelated environmental conditions, cause diverse impacts on ecological resources. Prior to European settlement, the tidal portion of the BCSA was a freshwater tidal marsh and swamp (cattails and Atlantic white cedar). Until the early 20th century, modifications to the wetlands primarily came from tree clearing and drainage alteration (i.e., ditching) in the BCSA and throughout the Hackensack Meadowlands, and development was limited to the upland surrounding the wetlands. Development and landfilling activities in the mid- to late part of the 20th century resulted in extensive filling of wetlands in the BCSA—resulting in an approximate 60 percent reduction in wetland area during the 1900s. The net loss of marsh caused a significant reduction in the tidal prism and altered stormwater inputs to Berry's Creek.

Hydrologic modifications during the 1900s resulted in substantial reductions in freshwater flow and sediment inputs to the estuary. These modifications centered on the construction of BCC in 1911, which diverted most of the flow away from LBC and into BCC. Construction of three reservoirs (1923, 1956, and 1967) for water supply in the Hackensack River basin substantially reduced freshwater and sediment inputs from the upper watershed into the estuary. Other notable changes affecting hydrology in the BCSA include construction and maintenance of the East and West Riser ditches at the northern end of the study area, placement of tide gates throughout the BCSA, filling of wetlands, and the management of stormwater for the New Jersey Sports and Exposition Authority (NJSEA) complex.

The hydrologic modifications reduced freshwater flow in the Hackensack River and altered sediment transport, which, combined with the dredging of the Hackensack River in the lower portion of the estuary, facilitated encroachment of brackish water into the BCSA and caused major habitat transitions driven by increasing salinity. Up to the early 1900s, the BCSA was dominated by freshwater species (e.g., cattails and Atlantic white cedar). Within approximately 20 years of completion of the Oradell Dam at the head of tide in 1923, cattails, wild rice, and other freshwater wetlands plants were replaced by *Phragmites*. In addition, sea level rise contributes to ongoing changes to the hydrology and increasing salinity of the BCSA.

The development and industrialization of the BCSA, especially the lowlands, resulted in chemical inputs to the tidal zone from a full range of industrial, commercial, and sewage discharges. As early as 1900, a substantial amount of the upland above the 100-year flood zone was developed. By the 1930s, chemical and other manufacturing facilities were active in the BCSA watershed. The pace of industrialization and infrastructure development increased and continued into the 1950s and 1960s, which was accompanied by filling of large tracts of marshes in the 1960s to early 1970s. This trend is evident in COPC concentrations in sediment that peaked in the 1950s and 1960s and have been significantly declining in surface sediment since then. Based on a review of New Jersey Department of Environmental Protection (NJDEP) and EPA records, there are 3 Superfund sites, 171 known contaminated sites, and 42 permitted surface water discharges within the BCSA, as well as many unpermitted discharges that are frequently evident.

Waste disposal practices, particularly sewage discharges to the BCSA, had significant detrimental effects on waterway dissolved oxygen concentrations and the aquatic community; these effects were significant during the 19th and throughout the 20th century. Biological impacts from low dissolved oxygen caused by municipal sewage discharges were observed in the BCSA from approximately the 1930s to the early 1990s, particularly in UBC and MBC. Improved treatment and diversion of sewage out of the BCSA to the Hackensack River has resulted in measurable improvements in dissolved oxygen throughout the system, but dissolved oxygen concentrations that fall below the state water quality criterion of 4 parts per million are still periodically observed for extended periods in the summer months. Other sewage-associated parameters, such as ammonia, remain above toxic levels. Ongoing discharges by publicly owned treatment works and combined sewer overflows to the Hackensack River continue to contribute elevated levels of other sewage-associated parameters to the estuary, and analysis of recent data indicates that tidal influx of water from the river significantly contributes to the depressed dissolved oxygen concentrations in the BCSA, especially in the summer months.

In summary, the BCSA has undergone a series of changes at multiple scales, unrelated to the discharge of hazardous substances, that combined have resulted in the current physical, chemical, and biological conditions. Many of these conditions are typical of urban ecosystems and must be taken into account in future planning and management of the BCSA.

Tidal System Stability (Section 2-1; Appendix F and G)

A distinct characteristic of the BCSA is its physical stability. Despite the history of changes summarized above, multiple lines of evidence indicate that the physical configuration of the BCSA has remained highly stable over time.

Analysis of aerial photographs dating from the 1930s to 2014, supported by maps made as early as the 1800s, indicates essentially no change in main channel, tributary, and marsh outlines, except as caused by human actions (i.e., filling, channel straightening). Although major storm events (e.g., hurricanes, tropical storms, nor'easters) and human actions (e.g., bridge construction) can result in some sediment reworking and redistribution in localized areas of tidal waterways, the marshes are stable and not substantively impacted by these events. Monitoring before and after Hurricane Irene (2011) and Hurricane Sandy (2012) during the RI provided unique opportunities to directly measure the stability of the waterways and marshes. For example:

- The channel width and stability remained the same throughout the BCSA based on georeferenced aerial photographs, with only a localized exception near the West Riser tide gate.

- A sand layer was placed on pilot study plots in the Berry's Creek waterway and marshes before Hurricane Sandy. Observations before and after this historically large storm event (>500-year return frequency based on water elevation) indicated little or no movement of the sand plot materials (Graphic ES-3) despite the historic water heights of this flood event (Graphic ES-4). New fine sediments covered the plots after the high water receded following the hurricane.

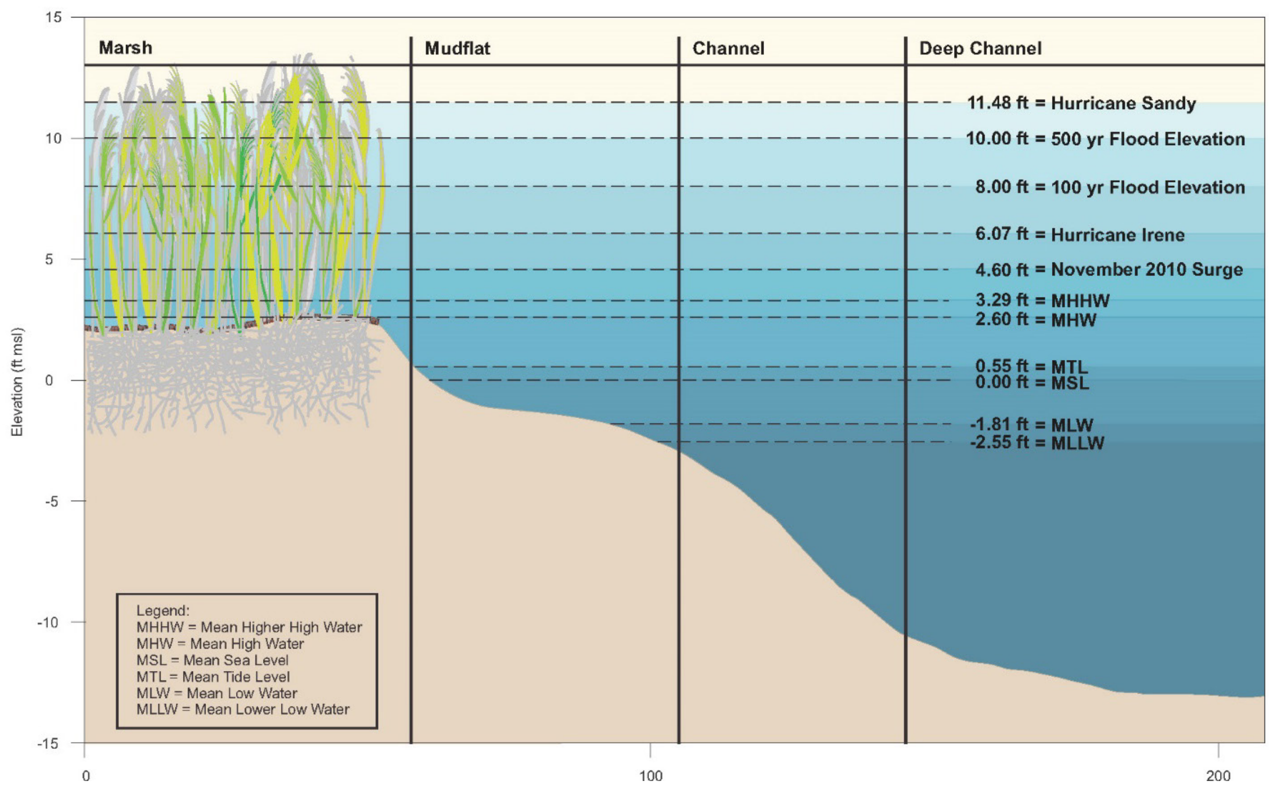
Graphic ES-3. Pilot Study Plots at East Riser Tide Gate Immediately Post-construction (A) and Following Hurricane Sandy (B)

Other lines of evidence demonstrating the stability of the marshes include:

- The elevations of two key marshes (Eight Day Swamp and Walden Swamp) have been increasing. This is based on yearly measurements of surface elevation tables by the Meadowlands Environmental Research Institute, even during the years of 2011 and 2012 when historic flooding occurred. These results support a finding of continuing steady net deposition of sediment on marshes over a wide range of conditions.

- Sediment has been and is being deposited (0.2 to 0.6 cm/year) in the marshes and the elevations in all of the major marshes have increased over the last 50+ years. This is based on the high resolution core analysis using cesium-137 radioisotope data.

- Storms such as Hurricane Irene and Hurricane Sandy lead to redistribution of some surface sediment in the BCSA. A comparative analysis of channel bathymetries measured in 2014 and 2008 found that detectable sediment accumulation and erosion (i.e., >1 ft.) had occurred in a small proportion of the BCSA main channel during the 6-year period between the bathymetric surveys. These changes reflect, in part, the collective influences of the two hurricanes (Irene and Sandy) and of Tropical Storm Lee that occurred during that period. Associated with and following Hurricane Sandy (a once in more than 500 years storm), a sediment influx was evident in the BCSA based on a relatively rapid accumulation of sediment on the pilot study test plots in UBC and MBC. Together, Irene, Lee, and Sandy cover the range of high intensity storm events expected to occur in the BCSA.



Graphic ES-4. Tidal Elevations in the BCSA during Typical Conditions and Major Storm/Surge Events

The *Phragmites* marshes are a key contributor to long-term system stability. The marsh structure (stem density, strength, height, and root mat) stabilizes main channel and tributary banks, dissipates energy within the system, and facilitates deposition and sequestration of sediments and other particulates within the marshes. Marsh vegetation in the BCSA has been composed predominately of *Phragmites* since before 1930 and has not changed since then in response to either anthropogenic activities or altered natural conditions (i.e., salinity increase). This attests to the contribution of *Phragmites* in maintaining the stability of the BCSA marshes. Several efforts to establish alternate vegetative communities within and near BCSA have largely failed (i.e., Berry's Creek Marsh, Kane Tract, Mill Creek), and to varying degrees these mitigation efforts have destabilized the marsh and resulted in extensive open water and mudflats.

Conceptual Site Model of Key Physical and Chemical Processes; Human Use and Ecological Receptors (RI Section 6 and Appendix H)

Through the course of the RI, many detailed conceptual site models (CSMs) and figures have been developed to describe the movement of water, sediment, and primary COPCs (mercury, methyl mercury, and PCBs) in the BCSA; promote an understanding of chemical fate, transformations, and biouptake mechanisms; and identify the potential human and ecological receptors. The most important connections between COPCs sediment, surface water, and receptors (human and ecological) in the BCSA are highlighted in Graphic ES-5. The following is an overview of the CSM graphic and key relationships related to the RI findings:

- The BCSA is an urban watershed divided into highly developed uplands and stable tidal lowlands, which are part of the Hackensack River estuary. As a side embayment of the Hackensack River estuary, the BCSA tidal area receives continuous sediment loading from the estuary but is not subject to the high velocity storm flows that occur along the main Hackensack River channel. The marsh vegetation (*Phragmites*) provides a high level of stability to the marsh and waterway banks, even during hurricane events.

- During non-storm conditions that occur the majority of the time, there is proportionately little upland input compared with the input from the main stem of the Hackensack River with the tidal flows; the tidal area of the BCSA is dominated by the flows associated with the tidal prism (approximately 90 percent) and the inorganic sediments (approximately 71 percent) that come into the study area from the estuary.

- The tidal zone comprises waterways and marsh habitats.

  - In the waterways, there are three distinct areas: intertidal mudflats (Graphic ES-5B), subtidal channels, and deeper pools that typically occur at bends in the channel.

- The marsh habitat is intertidal, with the degree of inundation varying with elevation (Graphic ES-5A, B, G, and H) and over the course of the month, neap to spring tide conditions. These large marsh areas generate an abundance of organic matter that originates as coarse particulate organic matter (CPOM) from the yearly senescence of *Phragmites* stems and leaves produced during the growing season (Graphic ES-5D). Some of this organic matter builds up on the marsh surface, covering the underlying sediment; some of it decomposes; and a large portion is observed throughout the year to float into the open water where it moves about the waterways, degrades into fine particulate organic matter (FPOM), and gets incorporated into sediment.

- The abundant organic matter derived both internally from the marshes and carried into the BCSA with tidal flow from the Hackensack River strongly influences sediment geochemistry leading to reducing conditions near the sediment surface. This generally limits the distribution of most macroinvertebrates to the top few centimeters of sediment and the overlying habitat (Graphic ES-5E, F, and G).

- The estuarine food web in the BCSA and surrounding region is defined, to a large extent, by the low and variable salinity and urban stressors such as upland runoff contaminants and sewage effluents, which dictate the species that can inhabit this urban estuary (Graphic ES-5F, G, and H).

  - Due to the abundant organic detritus material in waterways and marshes compared with benthic algae and phytoplankton, the BCSA food web is a detrital-based system, with *Phragmites* detritus accounting for most of the organic matter present in surface sediment and the water column fueling the food web. The detritus itself (CPOM) is much lower in COPCs than the inorganic fine particulates due to low uptake of COPCs into the leaves and stalks of the *Phragmites.*

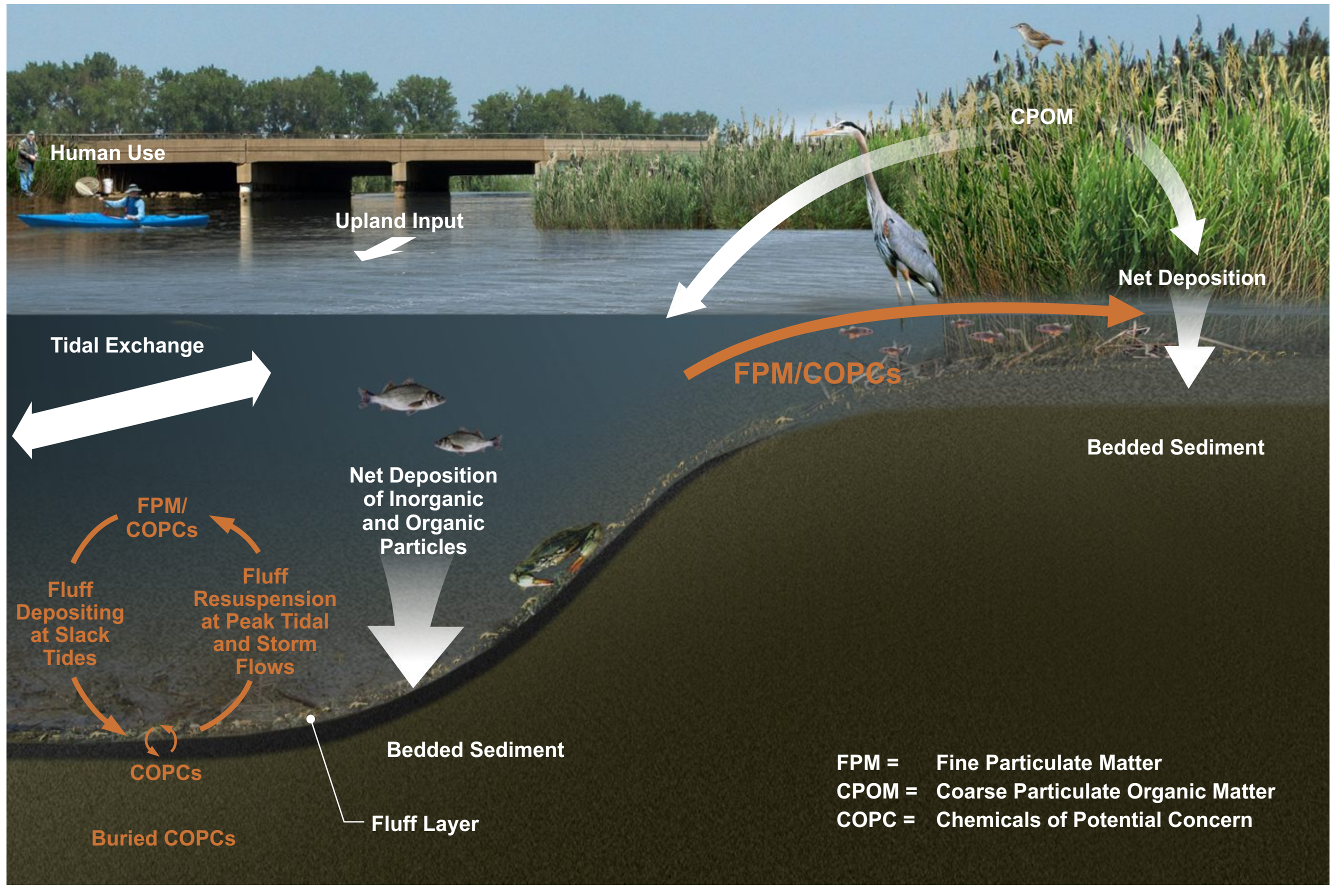
  - Detritus constitutes a large percentage of the suspended particulate mass in the water column and in the gut of BCSA fish. COPC concentrations on the detritus suspended in the water column (FPOM) are strongly influenced by concentrations of COPCs on the fine inorganic particulates that are associated with the sediment bed (see below).

  - The aquatic and semi-aquatic species ranging from microscopic organisms, macroinvertebrates, fish, and birds are all connected to the detritus-based food web. The distribution of marsh species changes with tidal conditions and seasonal patterns of activity. Also, migration occurs for some aquatic species (e.g., blue crab and white perch).

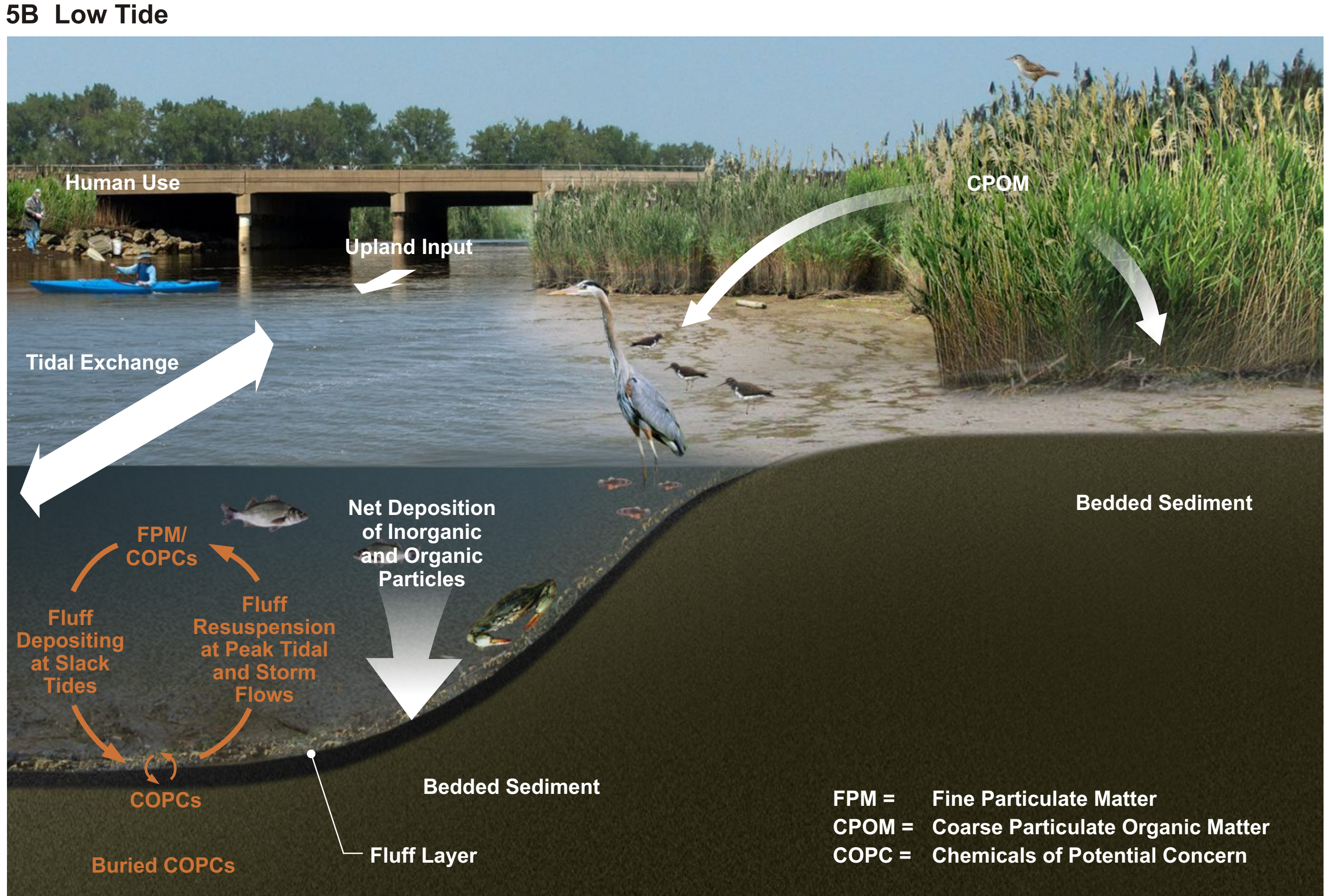
  - Relatively distinct groups of avian receptors inhabit the waterways and marshes. They include seasonal residents that migrate south during the winter. Other birds pass through the Meadowlands during migration to and from breeding areas to the north of the BCSA.

ES-5. BCSA Conceptual Site Model (CSM) of Key Physical and Chemical Processes; Human Use and Ecological Receptors

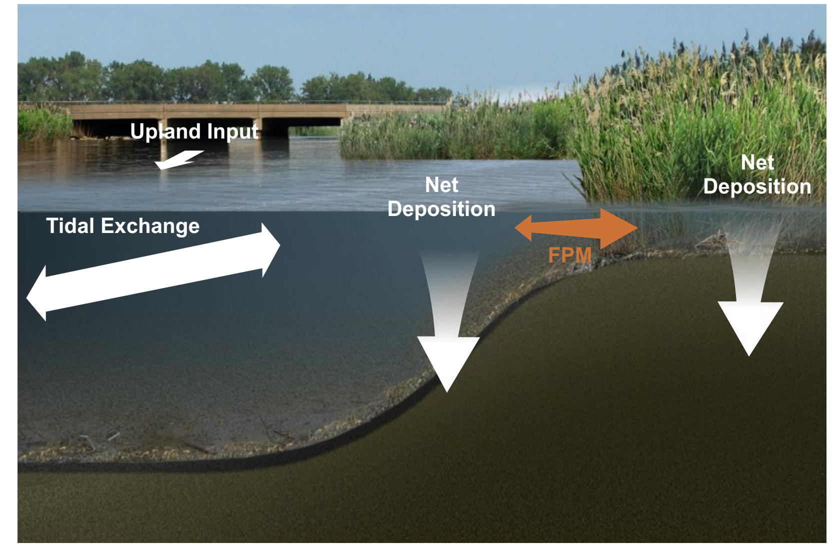
5A High Tide



5B Low Tide

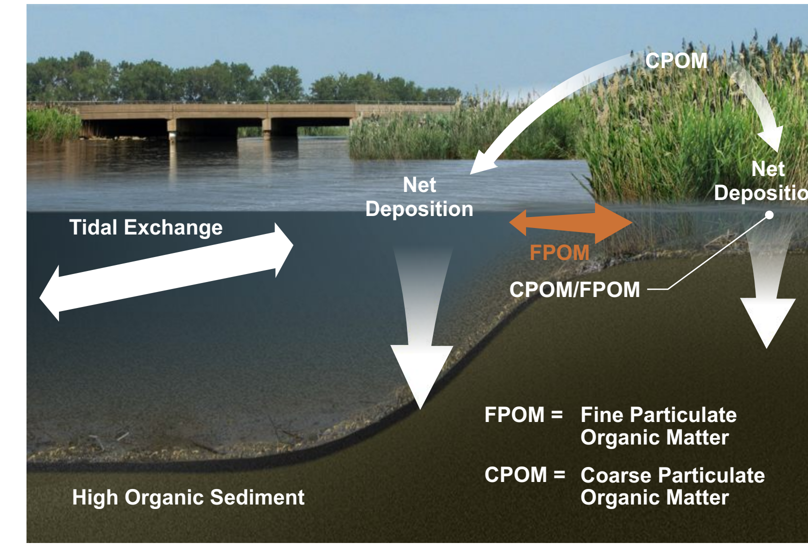


5C Inorganic Particulates Movement and Deposition



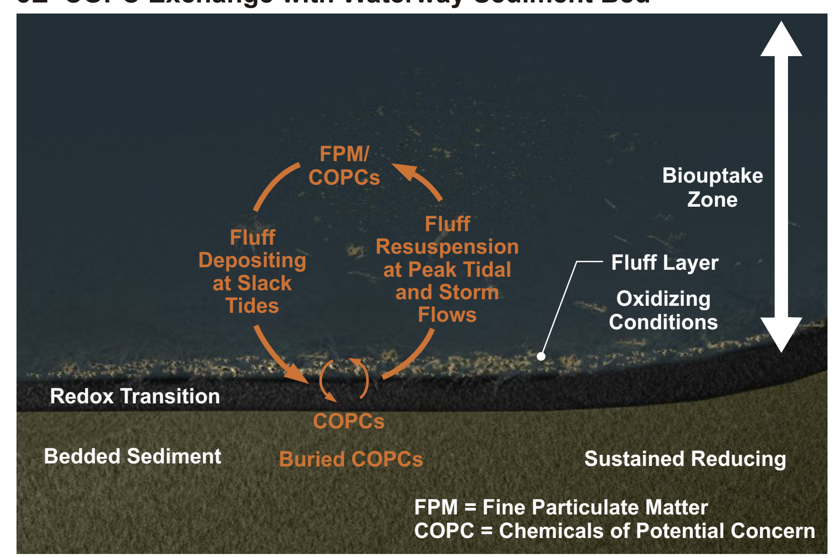
Dominant source is Hackensack River and primary sink is the marsh areas

5D Organic Particulates Movement and Deposition



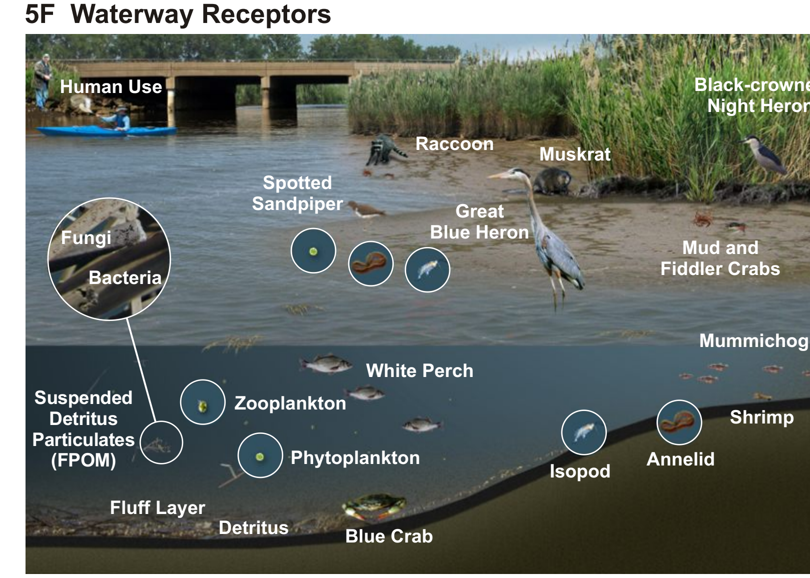
Dominant source is marshes in BCSA

5E COPC Exchange with Waterway Sediment Bed



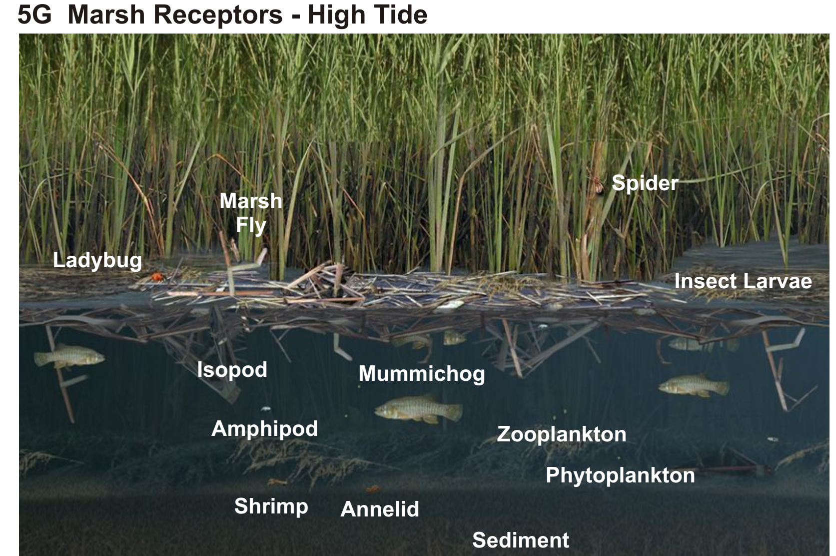
Limited exchange of COPCs in waterway sediment with area of biouptake; thin FPM "fluff layer" (<0.5 cm) is where physical and chemical processes control the exchange.

5F Waterway Receptors



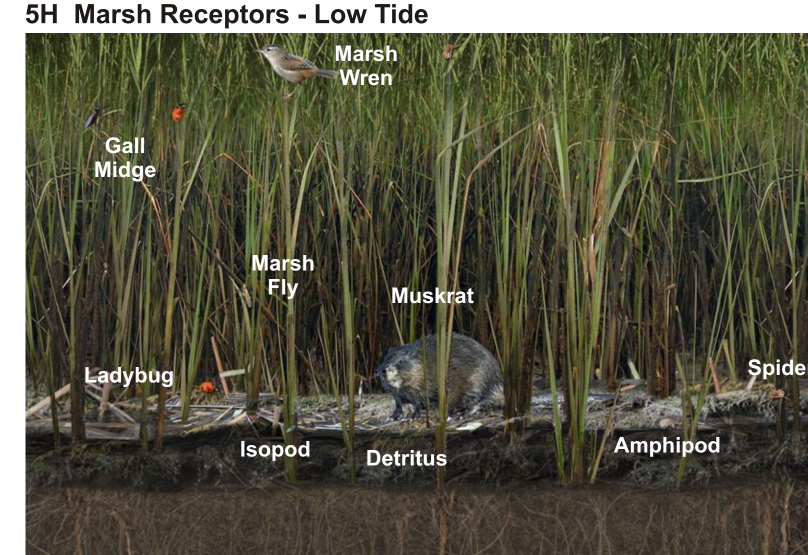
Detritus based food web

5G Marsh Receptors - High Tide



Some waterway species move into marsh and up plant stalks during high tide

5H Marsh Receptors - Low Tide



Receptor activity primarily on vegetation, detritus on surface of marsh and top 2 cm of sediment

- The industrial sources of COPCs were largely removed and controlled in the 1970s to early 1980s. Similarly, minimally treated sewage effluents were removed from the BCSA by the early 1990s. Some typical urban pollution sources remain, such as runoff from roads, unpermitted oil dumping to stormwater piping, permitted discharges, and atmospheric deposition.

- Secondary sources, such as surface or near surface sediment in UBC and MBC waterways containing COPC concentrations well above regional conditions (Graphic ES-5A, B, and E), are remnants of past primary sources and can still act as a secondary source of COPC contamination to marshes and downstream study segments.

- Movement of COPCs into surface water occurs through resuspension of particulates from a thin (~0.5 cm) fluff layer of unconsolidated materials on the surface of the sediment bed during flood and ebb tides and episodic storm events (Graphic ES-5A–C).

- Mercury is strongly associated with particulate matter. This, in combination with well-understood geochemical processes and site-specific conditions, limits the availability of mercury for methyl mercury production and bioaccumulation. A large portion of mercury in sediment is strongly bound to minimally soluble, sulfide phases, limiting the availability of mercury for methylation and, in turn, the bioavailability of mercury to benthic and aquatic organisms. Peak methyl mercury concentrations typically occur at or near the surface of the waterway sediment and as a diffuse peak across a depth horizon of 10 to 20 cm in marsh sediment due to the influence of dissolved oxygen supplied to the subsurface by tidal saturation/desaturation and oxygen release from the *Phragmites* roots. As such, exposure of organisms to methyl mercury produced in the marsh is limited because the macro-organisms are on the surface and peak concentrations occur at depth.

- PCBs also are strongly associated with sediment particulate matter, which is characterized by high organic matter concentrations in the BCSA. Binding of PCBs to organic matter limits the concentrations of freely dissolved PCBs and the bioavailability of PCBs to ecological and human receptors.

- COPCs in the water column are mixed with sediment originating from upland runoff (approximately 26 percent on average) and Hackensack River sediment (approximately 74 percent on average) (Graphic ES-5C). The upland runoff component is highest (most important) in the northern portion of the study area while the river component is highest (most important) in the southern end, with a blending of both occurring throughout the tidal area (Graphic ES-5A–B).

- Most of the COPCs in the water column are adsorbed to fine inorganic and organic particulates that are periodically carried with the tides from the waterways into the marshes where they are deposited in response to lower velocities and high surface areas of marsh vegetation (Graphic ES-5E).

- The amount of COPCs carried into the marshes during flood tide and retained is far greater than the amount of COPCs carried back out of the marshes during ebb tide, consistent with the multiple lines of evidence of continuous and stable accumulation of sediment in the marshes (Graphic ES-5C–D). Thus the marshes act as long-term sinks for deposited particulates and associated COPCs.

- Uptake of COPCs at the base of the food web occurs primarily by exposure to fine particulates in the water column that have been resuspended from the surface of the waterway sediment bed when water velocities are more elevated during tides and storm flows (i.e., precipitation and storm surge events). Organisms larger than plankton and benthic organisms, such as mummichogs, are exposed to COPCs primarily through their diet in the water column and surface of the sediment bed (Graphic ES-5A, B, and E).

  - COPC uptake in waterway biota appears to be mediated through a detritus-based food web, with *Phragmites* detritus from the surrounding marshes supplying the particulate organic matter that fuels the base of the BCSA food web. Shrimp, mud crab, and other organisms feeding on detritus and other FPOM provide the dietary link between detritus and fish and other consumers. Marsh detritus and other particulate organic carbon contribute to the fluff layer particulates at the surface of the waterway sediment bed, where they sorb to COPCs through interaction with the bed. COPCs enter the base of the food web as particulates in the fluff layer and are resuspended to the water column by tidal actions and storm flows.

  - Exposure and uptake by some ecological receptors in waterways are linked to the intertidal mudflats where receptors such as fiddler crabs, mummichog, shore birds, and wading birds are most active. The mummichog move into and out of the marshes during high tides.

  - The infaunal benthic organisms in the marsh sediment are highly limited and so uptake by ecological receptors in marshes occurs primarily above the sediment bed, on the overlying detritus and *Phragmites* stems and leaves. Concentrations of COPCs in these marsh exposure points are much lower than in waterway mudflats and marsh sediment.

  - White perch are the primary fish species that may be consumed by fisherman in the BCSA. They overwinter in deeper water areas outside of the BCSA and move into the BCSA during warm weather months to breed. Uptake of certain COPCs by white perch in the study area added to uptake from regional sources resulting in concentrations greater than the regional condition in UBC and MBC.

- Human activity in the tidal zone has been studied and found to be relatively infrequent and limited by the thick *Phragmites* vegetation, small areas of upland access, and shallow water in much of the waterways, especially in UBC and MBC. Primary access to the waterways occurs adjacent to roadways/bridges. Less frequent access occurs via boats/kayaks, mainly in BCC and LBC (Graphic ES-5A–B).

COPC Distribution and Movement (RI Sections 3, 5, and 6, and Appendices E, F, I, L and M)

The primary focus of the RI is to characterize 1) the nature and extent of site-related COPCs including their distribution across media in the waterways and marshes, 2) the physical system and linkages between the marshes and waterways, and 3) COPC distribution in biota and the pathways that can contribute to COPC biouptake and bioavailability. RI sampling activities were primarily completed within the tidal portion of the BCSA. Limited sampling was performed in the backwater areas above tide gates, consistent with the AOC/SOW.

Each of the primary COPCs can accumulate in biological tissue. In addition, methyl mercury and PCBs have been shown elsewhere to biomagnify in food webs, usually reaching higher concentrations in predators than their prey. Sampling conducted during this RI was designed to assess the chemical accumulation magnification and toxicity in BCSA biota and to define the linkages between COPC concentrations in abiotic (e.g., sediments, surface water) and biotic (e.g., plants, fish, birds) compartments. In addition, sediment toxicity testing was conducted to evaluate the effects of all contaminants combined by means of standard laboratory tests.

Other metals (e.g., aluminum, cadmium, chromium, manganese, nickel and zinc) and some organic chemicals (e.g., polycyclic aromatic hydrocarbons) have been detected in BCSA and have been identified as COPCs in the risk assessments. These compounds, however, contribute less to overall site risks. Further, the distributions of the majority of these minor COPCs mirror that of the primary COPCs. For these two reasons, the RI focuses on the primary COPCs. The distribution of the other COPCs relative to the distribution of primary COPCs is evaluated separately in the surface water, sediment, and biological sampling appendices (Appendices E, F, and I). Risks are assessed in Appendices L and M, which are pending submission in August and September 2016.

The RI fieldwork and laboratory testing were completed in accordance with the EPA-approved work plan documents. Table ES-1 provides a summary of the investigation work performed as part of the RI. A more comprehensive description is provided in Section 3 of the RI and Appendix C.

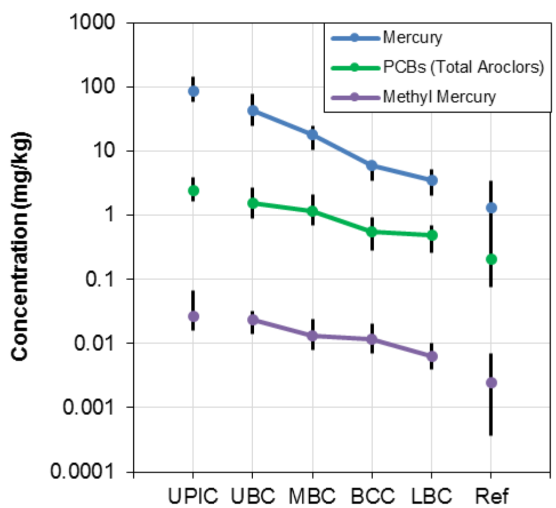
Table ES-1. Summary of RI Samples Collected, 2008–2015

Study Area	Media				Total Samples
	Sediment		Surface Water	Tissue	
	Waterway	Marsh			
Above Tide Gates	254	56	441	23	774
UBC	1,005	442	1,182	348	2,977
MBC	1,075	332	1,008	360	2,775
BCC	373	67	487	241	1,168
LBC	403	224	359	291	1,277
BCSA Subtotal	***3,110***	***1,121***	***3,477***	***1,263***	***8,971***
Reference Areas	65	131	368	754	1,318
Total	**3,175**	**1,252**	**3,845**	**2,017**	**10,289**

Notes: Total sample count does not include samples collected by Honeywell at the Universal Oil Products Site or by Morton International as part of their pilot studies, or Treatability Study-Pilot Study samples.

<u>Distribution of COPCs in Sediment (RI Section 5 and Appendix E and F)</u>

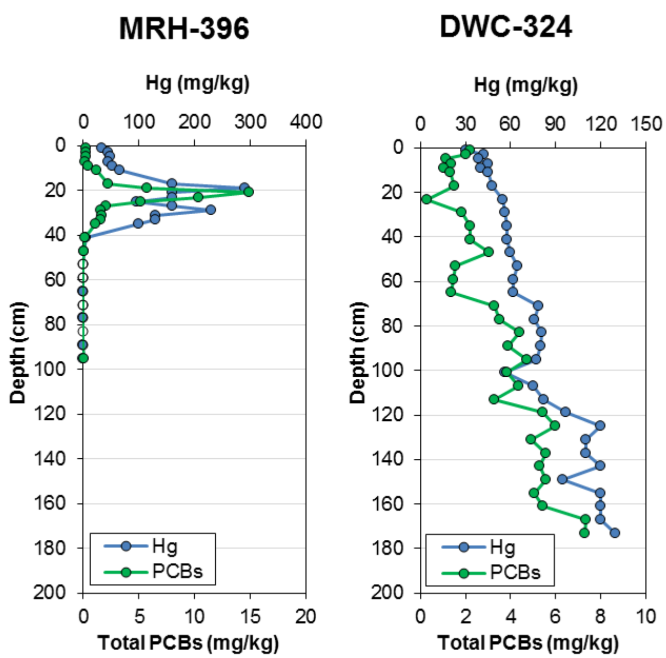
The distribution of the primary COPCs in BCSA sediment reflects historical industrial sources, sewage plant discharges to the BCSA tidal zone and surrounding watershed, and the net result of freshwater and tidal water interaction (Graphic ES-6). The net deposition of COPCs to the sediment is determined by the physical characteristics that dictate water flow and sediment transport within the BCSA, and the chemical characteristics of the COPCs—most notably their strong association with particulates.



Graphic ES-6. COPC Concentrations in Waterway BAZ Sediment (Median, 25th, and 75th Percentiles)

The higher residence time and closer proximity to the primary sources, in large part, resulted in the particulates with higher concentrations of mercury and PCBs being deposited in the upper reaches. These and other factors (e.g., high organic content of suspended solids) all contribute to the general pattern of COPC concentrations decreasing from north to south, with surface concentrations in BCC and LBC approaching regional conditions. Methyl mercury exhibits the same general north-to-south gradient of decreasing concentration in surface sediment; however, the relative difference in concentration from the upper to lower reaches is less pronounced, because methyl mercury is subject to varying dynamics affecting methylation of inorganic mercury.

COPC concentrations in particulates depositing to BCSA sediment have substantially decreased as historical sources in the BCSA and throughout the region have been decommissioned and mitigated. Accordingly, surface sediment COPC concentrations have progressively decreased from historical maxima at depth as a result of ongoing deposition. At nearly all locations, lower concentrations of COPCs are evident in the most recently deposited sediments compared with deeper depth at the same location. This pattern of natural recovery is consistently evident in all high-resolution sediment cores from the marshes and a majority of cores from the waterways (Graphic ES-7). The notable vertical profile exception is UPIC, where most marsh cores have the highest total mercury concentrations within the top 10 cm. The placement of a tide gate in 1967–1968 on Peach Island Creek near Gotham Parkway cut off most sediment from the tidal flows, thereby reducing the amount of sediment deposition and slowing the rate of burial of historical contamination. In addition, the changes in hydrology likely led to some compaction and compression of sediments in UPIC.



Graphic ES-7. Vertical Patterns of Mercury and PCBs in Marsh (left) and Waterway (right) Sediment

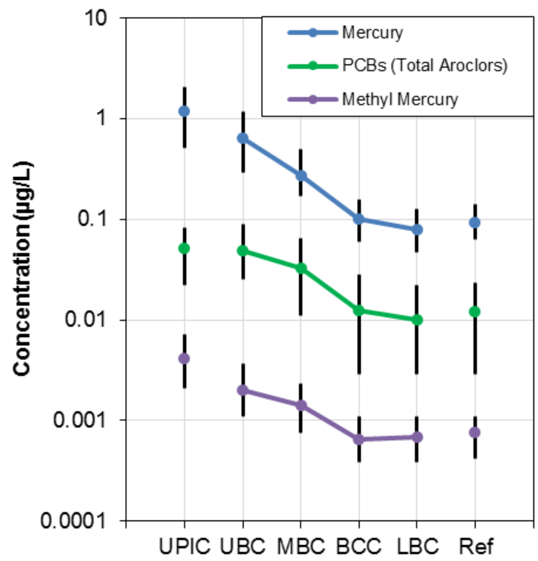
Vertical profiles of mercury and PCB concentrations in waterway sediment are more variable than in the marshes. This is due to varying sediment processes; episodic resuspension of surface sediment in response to localized velocity profiles during relatively rare, large storm events and localized anthropogenic activities (e.g., bridge building); and variations in sediment supply and deposition over time. These patterns are evident in the COPC profiles measured in high-resolution cores (Attachment F1 of Appendix F) and in the comprehensive inventory of all of the sediment mercury and PCB concentration data provided in Attachment F6 of Appendix F. The vertical profile patterns for methyl mercury and manganese in sediment vary somewhat from other COPCs because these are strongly influenced by geochemical factors, which differ between waterway and marsh sediments. Methyl mercury concentration peaks in waterway sediment are typically in the top few centimeters, while in the marshes the peak typically occurs at depths greater than 10 cm below the surface. Due to geochemical factors, manganese concentrations peak at the surface of the marsh sediment and may limit mercury methylation near the surface of the marsh.

<u>Distribution of COPCs in Surface Water (RI Section 5 and Appendix E)</u>

Tidal processes have both direct and indirect influences on surface water quality in the BCSA. Based on monitoring in 2009 through 2011, salinity decreases from mesohaline conditions in the lower BCSA reaches near the exchange points with the Hackensack River (typically in the range of 6 to 8 parts per thousand, ppt) to oligohaline conditions in the upper reaches (3 ppt in UBC) where the relative freshwater influence is greatest. Salinity levels in the BCSA and in the Hackensack River estuary appear to have been on the rise in recent years based on observations during the BCSA RI and data collected along the Hackensack River by the Meadowlands Environmental Research Institute.

Regional influences on surface water quality are most prominent in LBC and BCC, and surface water COPC concentrations in these reaches are similar to those seen in the reference sites. The residence time of water is multiple days in UBC during non-storm conditions and decreases to the south where the residence times in both BCC and LBC are less than one day. The middle and lower reaches of MBC are a mixing zone between the infrequently exchanged UBC and upper MBC and the frequently exchanged BCC. Water in LBC is similar to BCC and exchanged with the Hackensack River on a daily basis with the tides.

Broadly speaking, a north-to-south gradient of decreasing COPC concentration is observed in surface water that follows a similar spatial pattern observed in site surface sediment (Graphic ES-8). However, COPC concentrations in surface water at any given location can vary by as much as an order of magnitude over short time scales (hours, days) as a result of tidal water movement and particulate resuspension/deposition processes, countering the broad trend.

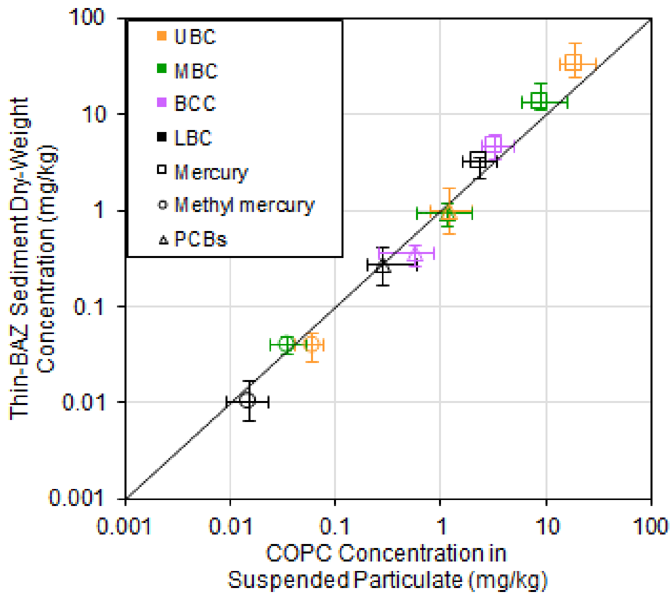


Graphic ES-8. COPC Concentrations in Unfiltered Surface Water (Median, 25th, and 75th Percentiles)

Comparison of results in paired unfiltered and filtered samples collected over the course of the RI shows that the primary COPCs are principally associated (>78 percent) with the particulate phase in BCSA surface water and are strongly influenced by routine and episodic particulate resuspension and deposition processes. Suspended particulates deposit to, interact with, and resuspend from the surface of the sediment bed in the waterway and tributaries in response to fluctuations in channel velocities and other processes such as wind-driven wave action and direct rainfall on exposed mudflats.

Surface water particulate COPC concentrations are closely related to COPC concentrations at the surface of the waterway sediment bed. On a tidal reach basis, there is a 1:1 correlation between COPC concentrations at the surface (0–2 cm) of the waterway sediment bed and the total COPC concentrations in particulates suspended in the surface water column (Graphic ES-9).

A thin (~0.5 cm) layer of unconsolidated particulates (the fluff layer) is present on the surface of waterway sediment bed as a result of deposition of particulates from the water column. COPCs are exchanged from the waterway sediment bed to these particulates. Then, when unconsolidated particulates are resuspended to the water column during periods of higher channel velocity, COPCs exchange with surface water (Graphic ES-5E). The cycle of unconsolidated particulate exchange between the water column and the surface of the waterway sediment bed is evident in multiple years of RI data sets and is a primary factor influencing the distribution and magnitude of COPC concentrations in BCSA surface water. As discussed below, this is also an important factor in transport of COPCs to the marshes in the system. These processes, coupled with fluctuations associated with tidal movement of water, can result in variation in COPC concentrations in surface water of over an order of magnitude on a routine basis (e.g., over the 6-hour period from high to low tide) and episodically (e.g., storm events).



Graphic ES-9. Comparison of COPC Concentrations in Surface Sediment to Concentrations on Particulates Suspended in Surface Water

Rare, major storm events, such as Hurricane Irene in August 2011 (a once in 100 years storm that resulted in 8.2 in. of rainfall in 24 hours) and Hurricane Sandy of 2012 (approximately a once in 500 years storm that resulted in a storm surge elevation of 11.48 ft above mean sea level or 8.88 ft above normal mean high tide) have a larger influence on BCSA surface water quality.

These rare major storms result in substantially increased delivery of sediment via surface water to the BCSA associated with the large volume of storm runoff and the tidal surge. In addition, the main channel and many tributaries are subject to more elevated water velocities during major rainfall events (i.e., Hurricane Irene) as the large volume of uplands storm runoff drains through the system, leading to short-term increases in the mass of suspended sediment in the BCSA surface water.

During 2014 and 2015, a focused and intensive analysis of the surface water entering and departing the marshes from the waterways was conducted. The analysis employed both frequent discrete surface water sampling and advanced optical methods to improve the understanding of the exchange between waterways and marshes. These studies further documented that most of the COPC mass in surface water is associated with fine particulates and that the fine particulates are highly retained in the marshes. These results provide another line of evidence that the marshes are a sink for contaminants that associate with fine particulates, consistent with literature on marsh ecosystems.

Biota COPCs Distribution (RI Section 5 and Appendix I)

COPCs are the key chemicals in defining site risks, and each can accumulate in biological tissue. In addition, methyl mercury and PCBs have been shown, in multiple studies, to biomagnify in food webs, reaching higher concentrations in predators than their prey.

COPCs in Marsh Biota

The marshes are the primary source of plant organic matter to the detrital-based food web in the BCSA. The overall distribution of COPCs in the dominant marsh plant (*Phragmites)* tissue indicates that COPCs in marsh sediment are not being mobilized to significant levels into the food web via plant uptake. COPCs concentrations in *Phragmites* roots are a small fraction of that found in marsh sediment, and COPC concentrations in leaves and stems are even lower than those found in the roots.

The COPC concentrations in detritus are typically higher than in *Phragmites* leaves (live or dead) because detritus is a mix of higher COPC concentrations in particulates from the adjacent waterway sediment and lower concentrations in the *Phragmites* materials.

COPCs are accumulating at low levels in marsh invertebrates and display a pattern of decreasing average concentration from the upper to lower reaches of the BCSA. Concentrations in most reaches are not statistically different from those observed in marsh biota at reference sites. The marsh invertebrates inhabit the standing vegetation and also the detrital layer on the marsh surface. A greater diversity and density of invertebrates occurs above the detritus layer in both the BCSA and reference sites than within the marsh sediments, consistent with typical invertebrate distribution in marsh systems.

Sediment cores taken in the marsh surface (below the detrital mat) found few individual macroinvertebrates, and those that were found were limited almost exclusively to the top 2 cm of the core and were dominated by surface dwelling species such as snails. Consequently, the low biouptake in the marshes aligns with the occurrence of most biological activity at or above the marsh surface where the concentrations of COPCs are the lowest.

COPCs in Waterway Biota

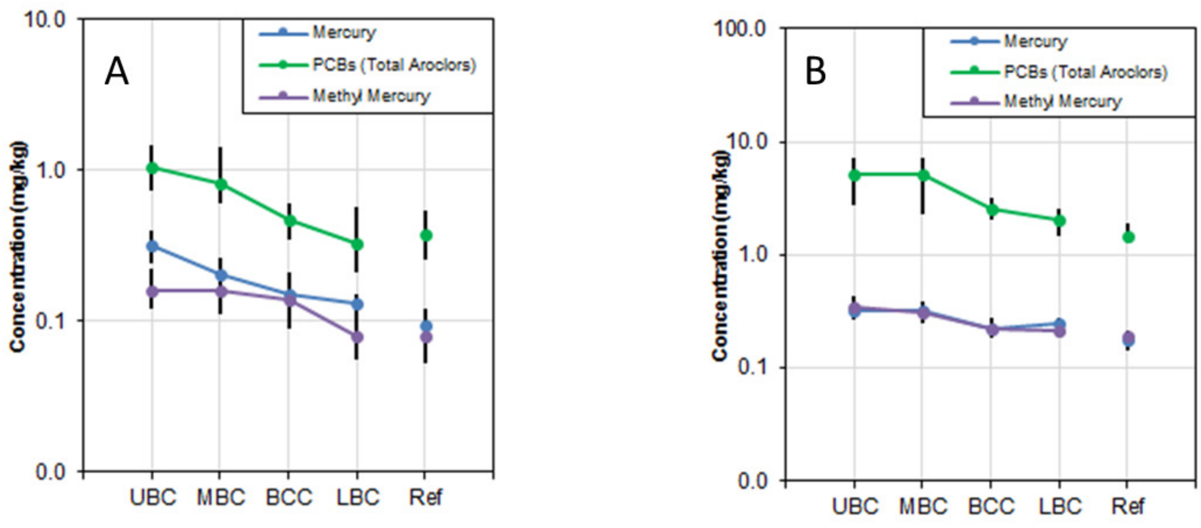
COPCs are accumulating in BCSA waterway biota. COPC concentrations are generally highest in white perch compared to mummichog and other sampled taxa, except for mercury in the fiddler crab and annelids in UBC. However, a portion of the body burden in white perch is present in reference area fish compared with other species, indicating some contributions from outside the BCSA.

Waterway biota COPC concentrations display a consistent pattern of higher concentrations in the UBC and MBC and lower concentrations in BCC and LBC (Table ES-2; Graphic ES-10).

Table ES-2. Median Whole Body COPC Concentrations in BCSA Reaches and Reference Areas

Reach	Concentration (mg/kg wet weight)								
	Mummichog			White Perch			Fiddler Crab		
	Mercury	Methyl Mercury	PCBs	Mercury	Methyl Mercury	PCBs	Mercury	Methyl Mercury	PCBs
UPIC	0.29	0.11	1.2	--	--	--	--	--	--
UBC	0.31	0.16	1.1	0.32	0.35	5.1	0.72	0.080	1.3
MBC	0.21	0.16	0.81	0.32	0.31	5.2	0.29	0.061	0.53
BCC	0.15	0.14	0.47	0.22	0.22	2.6	0.16	0.039	0.26
LBC	0.13	0.080	0.33	0.25	0.22	2.1	0.14	0.040	0.18
REF	0.095	0.079	0.38	0.18	0.19	1.5	0.092	0.027	0.24

Notes: All concentrations are for composited whole body samples. White perch data are for the target size (150–190 mm) samples.
-- = White perch and fiddler crab were not collected in UPIC.



Graphic ES-10. COPC Concentrations in Mummichog (A) and Whole Body White Perch (B) (Median, 25th, and 75th Percentiles)

Methyl mercury concentrations are higher in perch fillets than in whole body, while the opposite is true for PCB concentrations. Methyl mercury concentrations in the larger size classes of white perch are higher than concentrations in the fish collected as part of the routine site-wide monitoring in both the BCSA and reference sites. PCB concentrations in larger perch were lower compared to the routinely collected fish.

Natural Recovery and Integrative Analysis (RI Section 6 and Appendix F)

In the BCSA, considerable investigative activities have been directed toward evaluation of the sediment stability, natural recovery processes, and likely future rates of recovery. Site-specific natural recovery processes are known that reduce the toxicity through contaminant transformation, reduce bioavailability through increased adsorption, and sequester COPCs geochemically. These processes are fundamental to this fringing marsh system and will be sustained as long as the marsh and waterway ecosystem remains in place.

Consistent with its function as a fringing marsh system, the BCSA is highly stable, with only localized exceptions. Profiles of COPCs in site sediment cores indicate that the maximum concentrations of mercury and PCBs have been buried under cleaner sediment that has accumulated to varying degrees throughout nearly all of the BCSA waterways and marshes since the time when historical sources of COPCs were discharging. This pattern of broad recovery through burial by ongoing deposition across much of the system is consistent with other lines of evidence (e.g., deposition rates based on profiles of geochronological markers and surface elevation table data, sediment flux and trapping estimates, measurements of net particulate mass flux from the waterways to the marshes, and sediment transport modeling). The BCSA is accumulating sediment that generally contains far lower concentrations of the primary COPCs than historically deposited, deeper sediments.

Integrative analysis of physical and chemical sequestration processes that limit COPC bioavailability throughout the BCSA yields findings related to natural recovery:

- Abundance of organic carbon, clay, cation exchange capacity, sulfate, sulfides, and other related factors contributes to a reduction of inorganic and organic COPC bioavailability.
- The majority of mercury in sediment is present in low mobility/bioavailability fractions (50 to >70 percent is immobile/not bioavailable as mercury sulfides).
- Nearly all of the PCBs are bound to the particulates, which are high in organic content and are abundant throughout the BCSA.
- The limits on net methylation in the BCSA are due to a combination of factors and result in methyl mercury levels comparable to those measured at sites with much lower total mercury concentrations. This combination of factors include:
  - Intrinsic geochemical processes limiting mercury methylation noted above

- Concurrent high demethylation rates measured by other researchers
- Other site-specific factors influencing methylation such as manganese, iron, and sulfate, which variously support or inhibit methylation.

Particulate interaction between surface water and the surface of the waterway sediment bed is an important process influencing natural recovery. As described earlier, resuspension of particulates from the surface of the waterway sediment is an important secondary source of COPCs to surface water and, in turn, COPCs bound to particulates are transported with surface water to marshes and downgradient waterways.

As the COPC concentrations are generally higher in the waterways than marshes and the COPCs deposited in the marshes mostly originate from the waterway sediment, marsh natural recovery is directly related to the COPC concentrations at the surface of waterway sediment. This relationship is particularly significant in UBC and MBC, where the COPC concentrations in waterway surface sediment are significantly higher than the reference areas or regional conditions.

Consequently, natural recovery in marshes may be accelerated by reducing the concentration of COPCs in the surface sediment of the waterways in UBC and MBC. Also, biota tissue concentrations will likely decrease with continued decreases in surface sediment concentrations, by either natural processes or as a result of remedial actions. In addition, BCC and LBC COPC concentrations appear to be attenuating in a manner similar with regional conditions and may be accelerated by remedial actions in UBC and MBC.

Receptors and Pathways (RI Section 7 and Appendices L and M)

People can be exposed to COPCs via direct contact with sediment or surface water, inhalation, or ingestion of biota that has accumulated COPCs. Recreational users of the waterway are the primary human receptor group for the BCSA. Fishing, crabbing, and kayaking/canoeing are currently low frequency activities and are not expected to increase in the foreseeable future. Fishing and crabbing activities are focused in and around waterway areas that are accessible via upland features (e.g., bridges). Boat access to BCC from the Hackensack River also has been observed, with boat traffic mostly limited to BCC near the confluence with the river.

Wide fringing ditches and dense stands of *Phragmites* are barriers to human use of the marshes. Some contact with marsh sediments by recreational users can occur adjacent to waterway access points, but otherwise, recreational exposure in the marshes is highly unlikely and has not been observed. In the future, workers could contact marsh sediments during a construction project around or through them, though the nature of the construction would likely be of shorter duration compared to recreational exposures.

No residential exposure scenarios are complete within the BCSA waterways and marshes. Residential land use in the BCSA watershed is concentrated in the upland area, outside of the 100-year flood zone. Residential housing approvals closer to the tidal areas have been built, or are approved, in a manner that limits the potential for residential exposure scenarios. These residences do not have an existing or planned direct connection to the tidal waterways and marshes. Plus, dense marsh vegetation, soft sediments, and generally wide fringing ditches are in effect barriers that discourage access. Thus, any people living in such units would have an exposure scenario similar to the recreational scenarios. Commercial and industrial land use is concentrated around the tidal area. Local worker exposures would be similar to those of recreational users but may be less frequent.

A variety of ecological receptors can potentially be exposed to COPCs in both waterway and marsh environments. Avian receptors near the top of the BCSA food web are at greatest potential risk from exposure to biomagnifying compounds such as methyl mercury and PCBs via their diet, but all organisms may be exposed via direct contact with contaminated media (sediment and surface water).

The key ecological receptors in the BCSA waterway and marsh habitats (Graphic ES-5F–H) that are important to defining potential for risk are discussed in detail in the ecological risk assessment. COPC biouptake is linked to surface sediment and follows patterns observed in sediment. As such, COPCs in biological tissue are consistently higher in UBC and MBC where COPC concentrations are generally highest. Relationships between sediment and tissue concentrations are strongest in species with small home ranges (e.g., mummichog and fiddler crabs) but are also discernible in some of the more wide-ranging species (i.e., white perch).

<u>Risk Assessments (RI Section 7 and Appendices L and M)</u>

[To be added upon completion of the draft Ecological Risk Assessment and Human Health Risk Assessment.]

Human Health Risks (RI Section 7 and Appendix M)

[This summary section will be added upon completion of the Human Health Risk Assessment.]

Ecological Risks (RI Section 7 and Appendix M)

[This summary section will be added upon completion of the Ecological Risk Assessment.]

RI Summary of Key Findings

The following key findings from the RI have been compiled for ease of reference and to provide a framework of considerations in the evaluation of remedial alternatives in the FS:

1. The BCSA is an urban watershed with a stable tidal area. As a side embayment of the Hackensack River estuary, the BCSA tidal area receives continuous sediment loading from the estuary but is not subject to the high velocity storm flows that occur along the main river channel. The dominant marsh vegetation (*Phragmites australis*) provides a high level of stability to the marsh and channel banks, even during hurricane events.

2. COPCs include mercury, methyl mercury, and PCBs, which are the principal risk-driving chemicals. Other COPCs include metals and organic compounds.

3. COPC concentrations in sediment, surface water, and biota are substantially higher in the northern end of the study area and decrease approaching the Hackensack River.

4. COPC concentrations are lower at the sediment surface and substantially higher at depth. The highest COPC concentrations are typically buried by progressively cleaner sediment.

5. COPC biouptake is linked to the upper surface of the sediment bed and its interaction with the water column.

6. Natural conditions in the BCSA sequester COPCs and reduce bioavailability in sediment and surface water.

7. Waterway risks are elevated in relation to some EPA acceptable risk thresholds but are greatest in the northern reaches of the study area. Risks in the lower reaches are approaching reference site levels.

8. Multiple factors limit human use of the tidal zone (up to mean high water).

9. Ecological risks are more elevated in the waterways, in particular in the mudflats, compared with the marshes, where low COPC concentrations on the marsh surface limit exposures and risks.

10. Natural recovery of waterway sediment is occurring, but is limited by episodic reworking and resuspension of near-surface sediment in areas with elevated concentrations.

11. Marsh natural recovery is substantial and consistent across the site, but is limited by ongoing transport of COPCs adsorbed on particulates resuspended from waterway sediment.

12. BCC and LBC COPC concentrations in waterway sediment are attenuating consistent with regional conditions, which would be accelerated by remedial actions in the northern end of BCSA.

13. The work conducted over several years of RI field activities and analysis has led to a balanced and comprehensive understanding of contaminant distribution, fate, transport, and biological exposure processes. Confidence in these findings is high but some uncertainties remain. Initial risk reduction through remedial actions is best focused on those areas with higher risk and lower uncertainty. Future evaluation of remedial strategies will recognize the magnitude of uncertainties that are relevant and be designed, along with a post-remediation monitoring program, to reduce uncertainty so that at the end of the adaptive/phased remediation program the most efficient and effective remedy will have been implemented.

SECTION 1

INTRODUCTION

1.1 Statement of Purpose

The Berry's Creek Study Area (BCSA, or the site) Cooperating Potentially Responsible Party Group (hereafter referred to as "the BCSA Group") has entered into an Administrative Order on Consent (AOC) with the U.S. Environmental Protection Agency (EPA) Region 2 to perform a remedial investigation/feasibility study (RI/FS) pursuant to the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). The scope of the RI/FS is described in a statement of work (SOW) included as Appendix B to the AOC. As defined by the SOW, the purpose of the RI/FS is "to characterize the nature and extent of contamination as provided in this SOW and evaluate remedial alternatives that mitigate potential human health and ecological risks associated with the biouptake and environmental fate and transport of chemicals from historical and on-going sources of hazardous substance releases from various facilities, while taking into account other sources of chemical and non-chemical stressors and relevant background conditions."

During the development of the RI/FS Work Plan (BCSA Group 2009), a detailed set of conceptual site models (CSMs) of the physical, chemical, and biological components of the BCSA were prepared based on information and data available from prior studies. A series of 12 site-specific study questions were developed to direct and focus the strategic design of the field studies and subsequent analyses on key elements of the CSM. The analyses completed throughout the course of the remedial investigation (RI) were used to refine the physical, chemical, and biological CSMs. These CSMs provide a framework for evaluating the fate and transport of chemicals of potential concern (COPCs) and support the RI/FS objective of identifying an appropriate remedial action for the BCSA. Section 8 of this report presents a detailed discussion of the major findings of the RI in relation to the site-specific study questions.

1.2 Site Setting

The BCSA is an urban watershed located in the Hackensack River Meadowlands in Bergen County, New Jersey (Figure 1-1) within one of the most populous and urbanized regions of North America. The AOC defines the BCSA as "…the water body known as Berry's Creek, including the Berry's Creek Canal and the natural course of Berry's Creek; all tributaries to Berry's Creek from its headwaters to the Hackensack River; and wetlands that are hydrologically connected to Berry's Creek or its tributaries, all located within the boroughs of Rutherford, East Rutherford, Carlstadt, Wood Ridge, Moonachie, and Teterboro in Bergen County, New Jersey as depicted generally on the map attached as Appendix C, and any areas where contamination from the Study Area has come to be located" (USEPA 2008a).

EPA is using a watershed approach to address the BCSA, which is consistent with the Contaminated Sediment Guidance (USEPA 2005). The condition of the BCSA, therefore, reflects the combined contributions from multiple sources of contamination within a geographic area defined by the watershed, as opposed to chemical inputs from a single source. As a result, the BCSA's history differs from a typical CERCLA site where the site is confined to one or a few specific parcels or properties.

The BCSA Superfund site is defined by the 31 km^2 (12 mi^2) watershed of Berry's Creek situated along the middle of the Hackensack River estuary. The watershed consists of approximately 4.2 km^2 (1.6 mi^2) of tidal waterways and marshes (the "tidal zone") that are the focus of the RI/FS, and 27 km^2 (10.4 mi^2) of highly-urbanized uplands areas that drain to the BCSA tidal zone (Figure 1-2). The RI/FS is focused on the tidal zone, specifically characterization of contamination in Berry's Creek waterways and marshes, consistent with the AOC and SOW (USEPA 2008a).The main channel of Berry's Creek is an approximately 7.3-km (4.5-mile)[1] tidal tributary of the Hackensack River. Numerous tributary channels flow into the main channel, including the West and East Riser ditches, Nevertouch Creek, Eight Day Swamp tributary, Peach Island Creek (PIC), Ackerman's Creek, Rutherford and East Rutherford ditches, Fish Creek, and numerous smaller, unnamed tributaries. *Phragmites* marshes occupy 3.1 km^2 (756 acres)[2] of the BCSA.

The physical, chemical, and biological conditions of the BCSA reflect a balance of influences from the Hackensack River and freshwater upland inputs. Moving north (upstream) from the Hackensack River, the BCSA waterways narrow and become shallower. Also, salinities farther from the Hackensack River are much lower and freshwater conditions typically prevail (i.e., salinity <3 ppt[3]), especially following storm events. For the purposes of the RI/FS, Berry's Creek is operationally divided into five geographic study segments (Figure 1-2). The five segments are segregated by infrastructure and/or confluence with other waterways, and each has distinct hydrologic and geomorphic characteristics:

- Upper Berry's Creek (UBC), which starts at the West Riser tide gate and extends south to Paterson Plank Road

- Middle Berry's Creek (MBC), which extends from Paterson Plank Road to Route 3

[1] Measured from the West Riser tide gate to the confluence of BCC with the Hackensack River.
[2] Includes the BCSA tidal zone and Upper Peach Island Creek Marsh.
[3] New Jersey Surface Water Quality Standards define fresh water as that with a salinity less than 3 parts per thousand (ppt). New Jersey Administrative Code (N.J.A.C.) 7:9B

- BCC, which was constructed in 1911, and starts at Route 3 and terminates at the confluence with the Hackensack River
- Lower Berry's Creek (LBC), which is connected to the other study segments via a culvert at its northern end near Route 3 and to the Hackensack River at its southern end

Above Tide Gate Areas, including Upper Peach Island Creek (UPIC), the riser ditches, the Rutherford/East Rutherford ditches, and all other investigated areas upstream of the head of tide.

The study segments have different histories and hydrodynamic and sediment transport characteristics, which is reflected in the nature and extent of COPCs in tidal zone sediment. In addition, there are distinct differences between UBC/MBC and BCC/LBC. Generally speaking, UBC and MBC had a greater density of historical industrial and sewage discharge activity (Section 6.1), are more distant from the Hackensack River, and have less frequent tidally driven exchange with the estuary than BCC and LBC (Section 4.7.2). The West and East Riser ditches, UPIC, and Rutherford and East Rutherford ditches are located above tide gates and thus are less tidally influenced (except for backwater effects) depending on the functioning of the tide gates. Accordingly, the Above Tide Gate Areas are generally not considered to be tidal reaches of the BCSA.

The boundaries of the BCSA are defined by two sub-basins (02030103180060 and 02030103180070) of the New Jersey Department of Environmental Protection (NJDEP) 14-Digit Hydrologic Unit Code delineations for New Jersey, encompassing both the tidal area that is the subject of the RI/FS as well as the surrounding upland portions of the watershed. The BCSA uplands is dominated by industrial, commercial, and residential development and significant transportation corridors. Route 17, present along a majority of the northwestern side of the BCSA, provides a distinct separation between the predominantly industrial/commercial properties closer to the Berry's Creek tidal areas, and the predominantly residential properties of the communities of Hasbrouck Heights, Wood Ridge, and Rutherford (Figure 1-2). A ridge parallels Route 17 and, as a result, the residential areas are at a higher elevation than the adjacent industrial/commercial areas of the BCSA. For the most part, the residential areas are located above the 100-year flood zone elevation.

Watersheds that surround the BCSA are also densely developed and composed of mixed residential, commercial, and industrial uses. Outside of the BCSA, the Hackensack Meadowlands is composed of approximately 713 hectares (1,760 acres) of brackish marshes (HMDC 1984 in Kiviat and MacDonald 2002b). The Hackensack River is connected to Newark Bay, approximately 11.5 km (6.9 miles) downstream from the BCSA. The Oradell Dam is located approximately 12.3 km (7.4 miles) upstream from the BCSA (Figure 1-1) and exerts significant influence on the hydrology by restricting freshwater flow, thereby allowing upstream migration of the tidal front and increasing salinity in the Hackensack River and the BCSA. Two additional water supply reservoirs are located several miles upriver of the Oradell dam: Lake DeForest and Lake Tappan. These three reservoirs trap sediments and divert fresh water from the estuary.

1.3 Scope and Focus of Site Investigations

The primary focus of the RI was to characterize 1) the nature and extent of site-related COPCs including their distribution across media in the marshes and waterways, 2) the physical system and linkages between the marshes and waterways, and 3) COPC distribution in biota and the pathways that can contribute to COPC biouptake and bioavailability. RI sampling activities were primarily completed within the tidal portion of the BCSA, with limited sampling in tributaries above tide gates to evaluate inputs to the system, consistent with the AOC/SOW (USEPA 2008a).

To develop the scope of work for the RI/FS, the BCSA Group completed extensive research to identify and obtain reports relevant to the BCSA and Hackensack Meadowlands. Documents of interest covered topics ranging from ecosystem characterization to site-specific RIs, and included data and information published from 1930 to 2009. Materials were obtained from multiple agencies including EPA, U.S. Army Corps of Engineers (USACE), U.S. Fish and Wildlife Services (USFWS), National Oceanic and Atmospheric Administration (NOAA), NJDEP, U.S. Geological Survey (USGS), and the New Jersey Meadowlands Commission (NJMC)/Meadowlands Environmental Research Institute (MERI) through requests for file review pursuant to the Freedom of Information Act and New Jersey Open Public Records Act. The literature review also included peer reviewed literature and other technical documents through 2009, with periodic updates throughout the RI process. The document searches resulted in the collection of more than 700 documents for review. These materials were reviewed and synthesized as part of the scoping activities that preceded the RI field investigation (ELM 2007), and then were considered throughout the course of data analysis and ongoing scope development, as needed, to provide historical context.

The important data and conclusions from the earlier studies, as summarized in the literature review, formed the basis for development of the RI/FS framework, including:

- Development of CSMs to describe the movement of water, sediment, and COPCs in the BCSA
- Identification of potential ecological receptors and trophic relationships
- Understanding chemical fate, transformations, and potential biouptake mechanisms
- Design of study questions to guide the RI efforts.

The RI has been implemented using a phased approach in which the CSMs have been refined throughout the course of the investigation based on data analysis and information gathered in the preceding phase. The phases of the RI are summarized in detail in Section 3. An overview of the specific tasks is briefly provided here:

- **Scoping Activities (2008):** Focused on characterization of the physical template (i.e., bathymetry, sub-bottom profiling, historical aerial analysis); assessment of the biologically active zone (BAZ) using sediment profile imaging (SPI); water budget analysis; detailed literature review; initial development of CSMs for physical, chemical, and biological systems; identification of potential reference areas for further evaluation; receptor evaluation; and field and laboratory methods development

- **Phase 1 (2009):** Initial characterization of COPCs in waterway sediment, surface water, and aquatic biota; reference area characterization and selection; hydrodynamic and sediment transport measurements; aquatic community assessment; and COPC screening

- **Phase 2 (2010–2011):** Characterization of marsh sediments, and tissue concentrations, and more detailed characterization of horizontal and vertical distribution of COPCs in waterway and tidal tributary sediments; hydrodynamic and sediment transport measurements; characterization of marsh and waterway sediments using a diversity of methods to understand site-specific factors affecting bioavailability of COPCs; and aquatic and marsh community evaluation

- **Phase 3 (2012–2015):** Continued characterization of marsh and waterway sediments using a diversity of methods to understand site-specific factors affecting bioavailability of COPCs; collection of high-resolution cores to evaluate depositional patterns and natural recovery; food web analysis using stable isotopes, and tissue data from an expanded number of locations; focus on data collection to support fate and transport evaluation, especially potential exchange between marshes and waterways; and additional data collection to support risk assessments.

A full suite of chemicals was measured during the RI and evaluated as part of the risk assessment. Mercury, methyl mercury, and Aroclor PCBs have been identified as the predominant risk drivers for the BCSA (Section 7), and are collectively referred to as primary COPCs. The discussions throughout this report focus heavily on the primary COPCs. However, each of the chemicals that exceeded risk screening criteria (Table 1-1) are addressed fully in the risk assessments, and in other appendices where appropriate. These secondary COPCs do not contribute substantially to the understanding of the nature and extent of contaminant distribution in the BCSA because they are present infrequently, or at low concentrations relative to reference site conditions, or they co-vary with the primary COPCs.

Table 1-1. Summary of Chemicals of Potential Concern across All Media

Primary COPCs	*Pesticides*
Mercury	2,4'- and 4,4'-DDD
Methyl mercury	4,4'-DDE
PCBs (total Aroclors)	4,4'-DDT
Metals	Aldrin
Aluminum	Alpha-, Gamma-Chlordane
Antimony	Alpha-, Beta-, Delta- and Gamma-HCH
Arsenic	Dieldrin
Barium	Endosulfan II
Beryllium	Endosulfan sulfate
Cadmium	Endrin
Chromium (VI)	Endrin aldehyde
Chromium (total)	Endrin ketone
Cobalt	Heptachlor
Copper	Heptachlor epoxide
Iron	Methoxychlor
Lead	*Semivolatiles*
Manganese	3,3'-Dichlorobenzidine
Nickel	Bis(2-ethylhexyl)phthalate
Selenium	Butyl benzyl phthalate
Silver	Di-n-butyl phthalate
Thallium	Di-n-octylphthalate
Vanadium	Diethyl phthalate
Zinc	Dimethyl phthalate
PAHs	Hexachlorobenzene
Benz[a]anthracene	Phenol
Benzo[a]pyrene	*Volatiles*
Benzo[b]fluoranthene	1,2-Dichlorobenzene
Dibenz[a,h]anthracene	1,2,3- and 1,2,4-Trichlorobenzene
Indeno[1,2,3-cd]pyrene	Carbon disulfide
PAH (HMW)	Trichloroethene
PAH (total)	Vinyl chloride

Notes:
DDD = dichlorodiphenyldichloroethane; DDE = dichlorodiphenyldichloroethylene; DDT = dichlorodiphenyltrichloroethane; HCH = hexachlorocyclohexane; HMW = high molecular weight; PAH = polycyclic aromatic hydrocarbons.

Throughout the RI, BCSA Group representatives met regularly with the EPA and other agencies to present scopes of work and review findings. Site visits via land and water have been conducted with agency personnel, and EPA's contractor conducted routine oversight of fieldwork. In addition, EPA and other agencies commented on the various deliverables, and BCSA Group responses to the comments were provided to EPA. A comments/response summary is provided in Appendix A, along with references to where the EPA comments on previous documents have been addressed in the RI.

1.4 Report Organization

The remaining sections of this report are organized around the following major sections:

- Section 2: Overview and Synthesis of Key Findings—provides a concise summary of the key findings of the RI study and integrated CSM (Section 6).

- Section 3: Study Area Investigation—provides a description of the objectives and tasks for each phase of the RI/FS.

- Section 4: Environmental Setting—identifies the defining characteristics of the BCSA in terms of watershed characteristics, land use, morphology, climate, ecosystems, cultural resources, and regional context.

- Section 5: Chemical System Characterization—describes the results of RI sampling for sediment, surface water, biota, and air, in the BCSA and reference sites.

- Section 6: Integrative Site Characterization—ties together the physical, chemical, and biological CSMs; reviews past and ongoing sources of COPCs to the BCSA; identifies the factors controlling COPC fate, transport, and biouptake; and assesses natural recovery.

- Section 7: Human Health and Ecological Risk—discusses COPC concentration-response relationships for biological metrics, and presents an overview of the ecological risk assessment and human health risk assessment findings.

- Section 8: Site-Specific Study Questions—presents the Study Questions from the RI Work Plan and describes the conclusions supported by RI data for each question.

- Section 9: References—provides full citations for the literature referenced in this report.

This RI Report is supported by a series of appendices that present detailed discussions of the data collected during the RI, as well as data analyses, modeling, and research that were performed as part of the RI. These appendices provide the technical basis upon which the findings presented in this RI Report were built and include the following:

- Appendix A: EPA Comment Response Summary—presents a compilation of EPA comments to RI-related work plans and reports and associated responses from the BCSA Group.

- Appendix B: Chronology of Natural and Anthropogenic Events—provides a chronology of important natural and anthropogenic events that influenced the BCSA and the region.

- Appendix C: Summary of Site Investigations—summarizes the investigations performed to characterize the BCSA both prior to and as part of the RI, and provides the work plan, work plan addenda, and quality assurance project plan for the RI.

- Appendix D: Urban Hydrology—presents a detailed analysis of data collected and modeling performed to evaluate upland baseflow, storm runoff, and groundwater flow.

- Appendix E: Surface Water Characterization—presents and analyzes the empirical and model-estimated surface water quality and COPC concentration data.

- Appendix F: Sediment Characterization—presents and analyzes physical, chemical, and geochemical data on waterway and marsh sediment.

- Appendix G: Hydrodynamics and Sediment Transport—presents and analyzes empirical data on BCSA hydrodynamics and sediment transport, and describes the development, calibration, validation, and analysis of hydrodynamic and sediment transport models for the site.

- Appendix H: Chemical Conceptual Site Models—presents detailed CSMs for mercury/methyl mercury and polychlorinated biphenyls (PCBs) based on information and data collected during the RI and available in literature.

- Appendix I: Biological Characterization of COPC Uptake—presents data and analyses characterizing COPC distribution and accumulation by BCSA biota.

- Appendix J: Reference Areas/Regional Background—provides an analysis of the BCSA reference site selection and of regional background conditions.

- Appendix K: Data Validation, Management, and Usability Assessment—summarizes the data validation results and data handling and treatment protocols, and provides a complete set of analytical data collected during the RI.

- Appendix L: Baseline Ecological Risk Assessment (to be submitted separately)—provides the baseline ecological risk assessment (BERA), including all supporting analyses.

- Appendix M: Baseline Human Health Risk Assessment (to be submitted separately)—provides the baseline human health risk assessment, including all supporting analyses.

- Appendix N: Human Use in the BCSA—presents the findings of camera surveys and field observations to document human activity within the BCSA to assist in understanding human exposure pathway completeness and exposure frequency.

- Appendix O: Atmospheric Mercury Monitoring Studies—presents the results of air monitoring for mercury in the BCSA reference site.

SECTION 2

OVERVIEW AND SYNTHESIS OF KEY FINDINGS

The RI for the BCSA has been conducted to characterize the source, distribution, and transport of contaminants within the study area and to identify the pathways by which those contaminants could reach human or ecological receptors. A preliminary CSM was developed during the scoping activities to outline the primary processes by which site-specific contaminants move from source to receptor (BCSA Group 2009). That preliminary CSM described factors predicted to influence distribution, transport, fate, and bioavailability of COPCs at the site, and, in turn, the pathways for human and ecological exposure. The various components of the CSM have been investigated and tested throughout the RI. Many of the initial hypotheses have been confirmed, while others have been refined. The current CSM reflects the cumulative understanding gained through evaluation of 7 years of data collection, as well as site-specific and literature-based analyses. Though the term *conceptual* is used as a term of art, the current CSM for the BCSA is based on a robust characterization of numerous site-specific factors and interpretation of multiple lines of evidence, as well as quantification of many key components and relationships.

Key findings from the RI analyses and an overview of the CSM are summarized below and discussed in more detail in the remainder of the RI report and appendices. Many of these key findings are presented in Figure 2-1. Section 6 integrates the collective information and provides a more detailed description of the CSM generated based on the RI.

2.1 Sources and COPCs

COPCs in the BCSA derive from multiple historical and ongoing sources. Direct discharges from historical industrial facilities and sewage treatment plants, along with other unpermitted discharges and releases from landfills, have contributed to chemical loading in the BCSA. Historically, much of the industrial activity, sewage discharges, and uplands baseflow and stormwater discharges in the BCSA were located in the upper reaches of the BCSA (i.e. UBC and MBC), an area documented in the RI to have elevated levels of a variety of metals and organic chemicals. Ongoing sources, including upland baseflow and stormwater runoff, permitted discharges, regional contributions associated with tidal flow from the Hackensack River, and atmospheric deposition also contribute to the current COPC concentrations in the BCSA.

Mercury, methyl mercury, and PCBs have been identified as primary drivers of potential site risks[4] and are the focus of the RI reporting. Each of these contaminants can accumulate in biological tissue. In addition, methyl mercury and PCBs have been shown to biomagnify in food webs,

[4] Refer to Appendices L and M.

usually reaching higher concentrations in predators than their prey. As is discussed in Section 1.3, various other chemicals have been identified as secondary COPCs (Table 1-1) and are addressed fully in the risk assessments[5], and in other appendices where appropriate. Sampling conducted during the RI was designed, in part, to assess the chemical accumulation and magnification in BCSA biota and to define the linkages between COPC concentrations in abiotic (e.g., sediments, surface water) and biotic (e.g., plants, fish, birds) compartments. In addition, sediment toxicity testing and benthic community surveys were conducted to evaluate the combined effects of all contaminants.

2.2 Physical System

Berry's Creek is a side embayment of the larger Hackensack River estuary, and the river exerts an important influence on physical, chemical, and biological conditions within the BCSA. Flow in the BCSA is tidally dominated, except during large (e.g., 2.7 to 4.2 in. events that occur an average of once every 1 to 5 years)[6] rainfall events. Sediment and water from the region are transported to the study area with tidal exchange. Water quality conditions in the region, including low dissolved oxygen, elevated ammonia, and pathogens, likely due to sewage discharge along the Hackensack River, affect water quality in the BCSA. Upland runoff also contributes fresh water to the BCSA waterways. Because of its location, UBC is more affected by upland runoff than the other reaches.

The BCSA tidal waterways and marshes are a net depositional environment (Figure 2-1). As a result, the majority of waterway sediment shows accumulation and natural recovery, with differences explainable by variations in morphology and proximity to upland discharges and the Hackensack River. Elevated shear stresses occur in waterways during large storm events (e.g., ≥3.6 in. events that occur an average of once every 3 years)[7] as a result of increased upland runoff. These elevated shear stresses are sufficient to cause short-term, localized reworking of the shallow bedded sediment. These localized disturbances, combined with longer term processes such as sea level rise, influence net sedimentation as well as COPC distribution and natural recovery rates.

The waterways are surrounded by large expanses of marshes dominated by the invasive form of the common reed *Phragmites*. The *Phragmites* marshes are an important factor controlling system stability and COPC fate and transport (Figure 2-1). The marshes, due to their higher elevation and presence of dense *Phragmites* stands with deep root structures, provide physical stability to the BCSA landscape. The stable geomorphology/landforms present for decades throughout the majority of the BCSA are projected to remain so into the future. Sediment accumulation is occurring throughout the *Phragmites* marshes. There is a net flux of inorganic sediment into the

[5] Refer to Appendices L and M.
[6] Based on 24-hour rainfall totals (Appendix D). The 2.7 in. event is estimated to produce a storm runoff volume approximately equivalent to the average neap tidal prism. The 4.2 in. event is estimated to produce a storm runoff volume approximately equivalent to the average spring tidal prism.
[7] Based on 24-hour rainfall totals (Appendix D).

BCSA derived from estuarine and upland sources, and, in turn, a net flux of inorganic sediment from the waterways to the *Phragmites* marshes. The *Phragmites* marshes also generate a substantial mass of organic matter through primary production, which results in organic matter accumulation in the marsh sediment. A large amount of this detritus is exported to the adjacent waterways, where it contributes to sediment deposition, influences chemical partitioning, and fuels the food web.

2.3 Chemical Distribution and Fate

Mercury, methyl mercury, PCBs, and secondary COPCs are detected in site sediment, surface water, and biota. Concentrations generally exhibit a north to south decreasing gradient, with higher concentrations in UBC and MBC compared to the lower reaches (BCC and LBC). COPC concentrations in surface sediment and surface water in the lower reaches reflect the net effect of twice-daily tidal exchange with the Hackensack River. COPC residues in these areas are at or are approaching reference site conditions. Throughout the BCSA, mercury and PCB concentrations are typically higher in waterways than in marshes.

COPC concentrations are lower in surface sediment at most locations compared with deeper increments, indicating natural recovery has occurred over time. The principal exception to this pattern is methyl mercury, which is at maximum concentrations within the sulfate reducing zone.[8] In the Berry's Creek waterways, the sulfate reducing zone is located at or very near the sediment surface (typically within the top 2 cm of sediment), but in marshes, the depth of the sulfate reducing zone is more variable and generally somewhat deeper (average of ~6 cm).[9] Also, higher concentrations of COPCs are found at the surface in some areas of the waterways that are subject to more variable and higher peak flows/velocities (e.g., Eight Day Swamp Creek). Additionally, peak concentrations occur close to the surface in UPIC compared to sediment within the BCSA tidal zone. The pattern in UPIC is likely attributable to reduced sediment loading following the 1967–1968 construction of the PIC tide gate[10], which has resulted in decreased sediment deposition in this area since that time.

Waterway surface sediment COPC concentrations are the product of ongoing deposition to the sediment bed, physical/biological mixing, and episodic redistribution in localized areas during large storm events, and are consistently more elevated relative to marsh surface sediment. The lower COPC concentrations in marsh surface sediment are due in large part to the contribution of cleaner organic matter to the sediment from marsh vegetation. The ongoing transport and retention

[8] Refer to Sections 3.3.3 and 4.1 of Appendix F.
[9] Refer to Section 4.1 of Appendix F.
[10] Refer to Appendix B.

of particulate-bound COPCs from the waterways to the marshes results in slower recovery rates in the marshes than might otherwise be observed.[11]

In surface water, the primary COPCs strongly partition to suspended particulate matter, which is high in particulate organic carbon (POC) as a result of detritus export from the surrounding marshes, and organic loading from other sources (e.g., tidal exchange with the Hackensack River).[12] The high-organic-content suspended particulates routinely deposit to, interact with, and resuspend from the surface of the waterway sediment bed as a result of fluctuations in tidal and storm velocities (Figure 2-1). These processes support the presence of a thin (~0.5 cm) layer of unconsolidated, high-organic-content sediment on the surface of the sediment bed in the waterways.[13] This layer, commonly referred to as the "fluff layer" is typical of estuarine systems (Maa and Lee 2002). Interaction of the fluff layer with the surface of the waterway sediment bed is an important mechanism for COPC exchange to surface water and, in turn, COPC transport within the system.[14] The suspended particulate matter, and associated COPCs, is also transported into the marsh during high tides where it is deposited on detritus and the marsh surface, thereby contributing to marsh surface sediment COPC concentrations.[15]

Organic matter partitioning, sulfide complexation, and binding to other mineral phases (e.g., iron or manganese oxides) all play an important role in the fate, transport, and bioavailability of COPCs in the BCSA. Bioavailability of the primary COPCs is controlled by partitioning to organic matter or complexation with sulfides. For inorganic mercury, the high levels of acid volatile sulfides (AVS) and organic matter create conditions that favor the complexation of inorganic mercury into forms that have limited availability for mercury methylation.[16] PCB partitioning to detritus and other forms of POC in the water column is an important factor in PCB fate and transport in the BCSA and helps to limit bioavailability.[17]

2.4 Biouptake

Mercury, methyl mercury, and PCBs have been detected in biota collected in both waterways and marshes, with the highest concentrations in the upper reaches of the system and lower concentrations in the lower reaches.

Accumulation of the primary COPCs in waterway biota appears to be mediated through a detritus-based food web, with *Phragmites* detritus from the surrounding marshes supplying the particulate

[11] Refer to Section 5.3 of Appendix E.
[12] Refer to Sections 3.5 and 4.1 of Appendix E.
[13] Refer to Section 3.5 of Appendix E.
[14] Refer to Section 4.3 of Appendix E.
[15] Refer to Section 5 of Appendix E.
[16] Refer to Section 4 of Appendix F.
[17] Refer to Section 2.5.5 of Appendix H.

organic matter that fuels the base of the BCSA food web. Shrimp, mud crab, and other organisms feeding on detritus and other POC provide the dietary link between detritus and fish and other consumers. Detritus originating from the marsh POC from other sources (e.g., Hackensack River) contribute to the fluff layer particulates at the surface of the waterway sediment bed, where they sorb COPCs through interaction with the bed. COPCs that enter the base of the food web as fluff layer particulates are resuspended to the water column by tidal action and storm flows. Thus, COPC concentrations in the detritus entering the food web are linked to the COPC concentrations at the surface of the waterway sediment bed, which are low relative to the concentrations at depth in the waterway sediments.

In marshes, exposure to COPCs is limited primarily to the detrital layer, where the majority of the biological activity is concentrated.[18] Marsh invertebrates and other organisms feeding on or in the detrital layer on the marsh surface can be exposed and COPCs have been detected in marsh invertebrates. Particulates transported from the waterway are likely an important source of COPCs present in marsh detritus. Though some COPCs accumulate in *Phragmites* roots, the data indicate that little of this is translocated to the above-ground biomass.[19]

Overall, low COPC residues in marsh detritus and the topmost layer of waterway surface sediment (compared to deeper sediments) limit the COPC residues available for uptake.

2.5 Receptors and Risk[20]

COPC transport and uptake in waterway biota is a primary pathway driving human and ecological risks at the site (Figure 2-1). Recreational users consuming BCSA fish and birds ingesting fish, invertebrates, and sediment are the receptors at greatest risk from COPC exposures. Overall, calculated risks are greatest in the upper reaches of the system compared to the lower reaches and higher in the waterways compared to the marshes. The dense vegetation within the marshes combined with access restrictions limits overall human exposures and risks, and the low COPC concentrations in marsh detritus compared to waterway sediments contributes to lower ecological exposures and risks. Exposure to COPCs at depth in the marsh sediments is limited given that little of the COPC levels at depth is translocated to the above-ground biomass.[21]

2.6 Summary

Overall, the data indicate that the BCSA is influenced by its interactions with the larger region. Twice-daily tidal exchange with the Hackensack River and upland input (particularly storm flows) influence the fate of COPCs historically deposited in the BCSA from a variety of industrial and

[18] Refer to Section 3.1 of Appendix I.
[19] Refer to Section 3.1 of Appendix I.
[20] Appendix L and Appendix M provide the complete baseline risk assessments.
[22] Refer to Appendix C.

other sources. The stable landscape created by the *Phragmites* marshes and the influx of inorganic sediment from the region has led to a system that is recovering from past COPC discharges. The highest COPC concentrations are typically found at depth in sediment, and ongoing sediment deposition is expected to continue as sea level continues to rise—resulting in ongoing burial of historical impacts with cleaner material. The morphology and vegetation of the BCSA have been resilient to past disturbances (i.e., wetland filling, development, etc.) and are predicted to remain stable as sediment deposition continues. Despite this natural recovery, COPCs in surface sediment, surface water, and biota in UBC and portions of MBC remain at concentrations that are well above reference site concentrations. Large storm events can cause localized resuspension of shallow sediment in the waterway that can result in some redistribution of COPCs and slow the recovery of marshes and other areas of the waterways.

The periodic resuspension of particulates from the fluff layer at the surface of waterway sediments and subsequent import of particulate-bound COPCs to the marsh during tidal flooding results in a continued source of COPCs to the marshes from the waterways (Figure 2-1). Fresh detritus from the marshes is low in COPCs, and contributes to the typically lower COPC concentrations in marsh sediments compared to waterway sediments. POC from the marshes, combined with POC and inorganic particulates carried into the BCSA from other sources (e.g., tidal exchange with the Hackensack River), forms the fluff layer at the surface of the waterway sediment bed. The detritus also fuels the food web. COPCs in waterway sediment and organic matter in surface water appear to be important sources contributing to COPC uptake in biological receptors.

People consuming fish, and wildlife foraging in the waterway, are the receptors at greatest risk from exposure to COPCs (Figure 2-1). COPC exposures and risks are predicted be higher in the upper reaches of the system compared to the lower reaches and higher in the waterways compared to the marshes, where dense vegetation and lower COPC concentrations in the detritus layer combine to reduce overall exposure.

SECTION 3

STUDY AREA INVESTIGATION

The BCSA RI was designed and implemented as an iterative, comprehensive characterization. It was sequenced to enable findings from each phase of investigation to inform progressively more focused study questions. The field and laboratory studies were designed to answer questions that emerged from the iterative data analysis, which took into account the entire data set available at the time. Numerous presentations of findings were made to EPA and other agencies to enable discussion of the results and obtain input on scoping of additional studies needed to answer the study questions and satisfy the AOC/SOW. This phased approach resulted in the collection of more than 10,000 samples of different media, including air, sediment, surface water, and tissue, providing substantial data to evaluate COPC distribution, fate, and transport; complete the risk assessment; and support the FS and the remedial decision-making process.

The RI fieldwork and laboratory testing were completed in accordance with the EPA-approved work plan, work plan addenda, and quality assurance project plan (QAPP). These documents and a comprehensive description of the RI sampling are provided in Appendix C. More than 10,000 samples were collected during the RI throughout the BCSA and reference sites (Table 3-1).

Table 3-1. Summary of RI Samples Collected, 2008-2015

Study Area	Media				Total Samples
	Sediment		Water	Tissue	
	Waterway	Marsh			
Above Tide Gates	254	56	441	23	774
UBC	1005	442	1182	348	2977
MBC	1075	332	1008	360	2775
BCC	373	67	487	241	1168
LBC	403	224	359	291	1277
BCSA Subtotal	***3110***	***1121***	***3477***	***1263***	***8971***
Reference Sites	65	131	368	754	1318
Total	**3175**	**1252**	**3845**	**2017**	**10289**

Notes: Sample count is for RI samples only and excludes treatability study / pilot study samples and samples collected by other parties as part of separate investigations at the Universal Oil Products (UOP) and Ventron/Velsicol Superfund sites, which are also located in the BCSA.

Each phase of investigation is summarized briefly below, with reference to relevant project documents.

3.1 Scoping Activities (2007–2008)

Nine scoping tasks were completed in 2007 and 2008 pursuant to an Interim AOC (July 13, 2007) and the EPA-approved Scoping Activities Work Plan.[22] The purpose of the scoping activities was to advance the understanding of the BCSA to support development of preliminary CSMs and refine specific study questions that must be addressed by the BCSA RI/FS to achieve its purpose. Data and information collected from these scoping tasks provided a foundation for defining the Phase 1 scope of work. The results of the scoping activities were integrated into the Phase 1 RI/FS Work Plan[23] and technical memoranda (BCSA Group 2009; ELM 2008). The components of, and key findings from, each of the scoping activities tasks are briefly described below.

Physical Template: The physical template is the base of the CSM upon which the chemical and biological elements are structured. The physical template characterization included a bathymetric survey, side-scan sonar survey, a magnetometer survey, sub-bottom profiling, and geotechnical testing of sediment cores. The objective of these studies was to develop an understanding of the bathymetry, texture, lithology, and thickness of soft sediment, as well as the presence of utilities and other artificial features in shallow waterway sediments. The bathymetry determined that the main channel shallows with distance from the Hackensack River, and the thalweg meanders within the banks. Shallow water depths were prevalent, particularly above Paterson Plank Road and in tributaries. Overall, generally fine grained sediment was evident throughout the study area, except for localized areas near meander bends and the confluences with some tributaries. Detailed mapping of the subsurface features was provided in the separate report of those activities (Earthworks and Rogers Surveying 2008).

Aerial Photograph Analysis: Historical aerial photographs from 1930 to 2002 were analyzed to assess upland development, wetland losses, and channel gains/losses in the BCSA. Channel morphology (e.g., meander wavelength, belt width) also was assessed in the main channel and selected tidal tributaries as a measure of system stability. The analysis identified more than 728 hectares (1,800 acres) of wetland/open water loss over the period of analysis due primarily to placement of fill for development. In addition, an overall loss of approximately 29.2 km (17.5 miles) of tidal tributaries was measured, even given increases due to construction of drainage ditches for mosquito control. The geomorphology of the main channel and tributaries was essentially unchanged over the period of analysis in spite of these alterations and the construction of numerous road crossings, installation of tide gates, hydrologic changes in the estuary (e.g., reduced freshwater flow), and significant storm activity over the period of record. The only area where marsh instability was observed was within the wetland restoration area for the former EnCap Golf LLC (EnCap) site in LBC (Figure 1-2), where *Phragmites* marsh was replaced with *Spartina* and other species, but transitioned over time to isolated vegetated patches interspersed by extensive

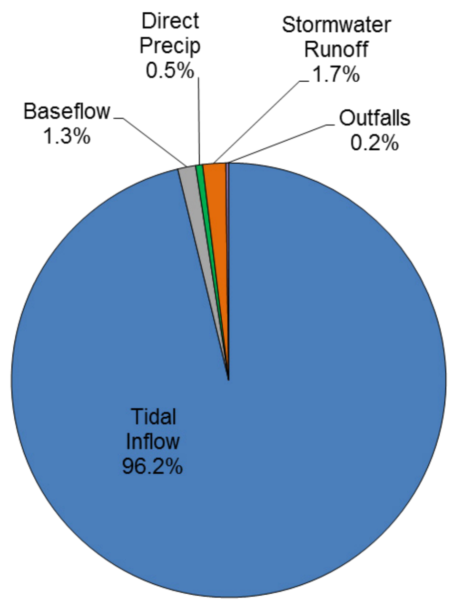
[22] Refer to Appendix C.
[23] Refer to Appendix C.

mudflats. However, the surrounding undisturbed marsh areas remained unchanged. These findings, in combination with other lines of evidence, support a conclusion that the BCSA is a stable landscape that is resilient to both natural and human-induced changes. Detailed descriptions of the aerial photographs were presented in a technical memorandum submitted to EPA (ELM 2008).

Study Area Reconnaissance: A series of reconnaissance visits to the site were conducted by land and by boat in 2007 and 2008. During these visits, the conditions were documented at approximately 20 locations in the BCSA, with representative photograph(s) and written general and location-specific survey forms that characterized the conditions and, in particular, noted evidence of releases (e.g., oil deposits, substrate discoloration, and sewage odors). In addition, limited human activity was noted in and around some localized areas along the waterways. The perspective gained from these activities supported development of the site-specific CSMs and informed fieldwork planning and work plan development.

Water Budget: A water budget was developed for the BCSA watershed, taking into account tidal input from the Hackensack River, as well as upland flow contributions, over a range of conditions. The purpose of this accounting was to understand the relative importance of these various components to system flows, and how the hydrodynamic system conditions vary 1) with spring-neap tidal phase, 2) with storm events, and 3) over the long-term development history of the system. These conditions exert significant influence on system hydrodynamics and, in turn, sediment and COPC transport dynamics. The analysis concluded that flow to the BCSA is tidally dominated and freshwater inputs to the BCSA are small by comparison (Graphic 1).

The tidal influence was predicted to be less in UBC than in other reaches, with multiple tidal cycles potentially required to fully exchange with the Hackensack River. Groundwater discharge is limited by the local hydrogeology (Section 4.7.2) and, as a consequence, freshwater baseflow to the tidal zone is small. The water budget analysis, together with the aerial photograph analysis (BCSA Group 2008), demonstrate that a substantial loss of tidal prism has occurred in the system over the past 100 years, almost exclusively as a result of urbanization and infilling of the marshes. A consequence of this loss is a reduction in system energy due to the reduced amount of water entering and exiting the system with each tidal cycle, which favors sediment deposition.



Graphic 1. BCSA Water Balance Based on Empirical Measurements and Model Estimates for the Period from May 2009 to October 2011

Data Compilation and Analysis: An analysis of searchable databases of relevant existing wells and spills/releases in the watershed, New Jersey Pollutant Discharge Elimination System (NJPDES) permits, and other relevant documents and information sources regarding available surface water, sediment, and biotic data was completed. File reviews and document requests were made of EPA, NJDEP, USFWS, NOAA, MERI, USACE, and USGS, resulting in a large number of documents containing additional data. A detailed summary of the data and documents reviewed was presented in the Phase 1 Work Plan. Historical data were subsequently considered in the Phase 1 Site Characterization Report (BCSA Group 2010) to perform an initial evaluation of long-term concentration trends. A summary of some of the more substantive (based on scope and design) pre-RI investigations that were reviewed and related references are provided in Appendix C.

Reference Site Identification: Reference sites are used as one point of comparison to discern potential site-related impacts from regional conditions or non-COPC stressors (e.g., salinity, low dissolved oxygen). Candidate reference sites were identified using a combination of geographic analysis and data review to identify sites with similar watersheds (area and land use), salinity ranges, geology, and plant communities. Sites were evaluated within the Hackensack Meadowlands, elsewhere in the greater Hudson-Raritan estuary area, as well as other estuaries up and down the Mid-Atlantic coast. Following the paper analysis, which screened the number of candidate sites to nine, site visits were made by two senior ecologists on the project team. This resulted in the further reduction of candidate sites to seven.

On June 2 and 3, 2008, representatives from the EPA, NJDEP, NOAA, USFWS, and the BCSA Group's project team toured the BCSA and then viewed the candidate reference sites. Based on the tour and discussions of the relative merits of the seven potential candidate areas, the participants agreed to four candidate reference sites for further evaluation in Phase 1: two sites in the Lower Hackensack River watershed (Mill Creek and Bellman's Creek), and two sites outside the Lower Hackensack River watershed (Woodbridge River and Richmond Creek). The analysis that led to the selection of these reference sites was summarized in a technical memorandum (ELM 2008) and addendum (ELM 2009) submitted to EPA prior to the start of RI activities. The reference sites were further investigated and refined during the RI.

Ecologically Relevant Receptor Identification: A literature review was completed to identify potential ecological receptors for consideration as measurement or assessment endpoints in the BERA. This analysis included identification of species that are likely present in the BCSA based on available community data from Berry's Creek and the Hackensack Meadowlands, and development of a conceptual food web for the BCSA. The results of this analysis were presented in Section 5.4 of the RI/FS Work Plan[24], where potential waterway and marsh receptors were described. The selected species included marsh vegetation, various birds, aquatic species (fish and crabs), and mammals.

Conceptual Site Models: Detailed CSMs were developed to describe physical processes, chemical fate and transport, biological systems, and potential exposure pathways, based on review of relevant literature regarding the Hackensack Meadowlands and other estuarine locations. The CSMs were used to identify study questions and develop the scope of work for the Phase 1 RI, and were presented in detail in the Phase 1 Work Plan.[25]

Methods Development: The BCSA Group prepared and implemented a Methods Development Work Plan[26] that was approved by EPA. The tasks performed per the work plan included evaluation of field and laboratory methods to evaluate logistical considerations, field sample collection methods, and potential laboratory sample preparation and analysis issues (e.g., tissue preparation, extraction techniques, and matrix interferences). The outcome of the methods development work was reflected in the proposed sampling and analysis approaches identified in

[24] Refer to Appendix C.
[25] Refer to Appendix C.
[26] Refer to Appendix C.

the Phase 1 Work Plan and QAPP and supported the development of safe and efficient field implementation approaches for Phase 1 of the RI.

3.2 Phase 1 (2009–2010)

Fieldwork associated with Phase 1 of the EPA-approved RI/FS Work Plan (approved May 8, 2009)[27] was implemented from spring 2009 through spring 2010. The Phase 1 RI work built upon the understanding developed during the scoping activities. Phase 1 focused on characterization of the horizontal and vertical distribution of COPCs in UBC, MBC, BCC, and LBC in waterway sediment, surface water, and tissue chemistry. In addition, initial characterization of the aquatic community was completed. In total, Phase 1 included eight tasks, of which four entailed field characterization in the BCSA (hydrodynamics, surface water, sediment, and biota), one addressed characterization of potential reference areas, and three involved reviews of existing information and further CSM development (groundwater, atmospheric deposition, and cultural resources). Analysis of Phase 1 data resulted in a refined COPC list that was used to focus future investigation work.

The following overview identifies the objectives of the Phase 1 sampling programs. A summary of all samples collected in Phase 1 is provided in Table 1 of Appendix C:

- The hydrodynamics task was designed to combine continuous hydrodynamic/water quality data collection in select locations with discrete data collection in a broader suite of locations. This task also emphasized detailed analyses of suspended sediment fluxes within the tidal system in the BCSA. Further development of the hydrodynamic and particulate transport CSM through this task was a primary goal of Phase 1.

- The surface water sampling task combined four quarters of ebb and flood composite water sampling[28] with discrete water sampling to achieve a balance between temporal continuity and spatial and analytical breadth. It included sampling in both typical dry weather conditions as well as storm events to assess weather-induced variability. Phase 1 also included characterization of marsh inundation using survey transects and piezometers to measure water levels over a range of tidal conditions.

- The sediment sampling program used a multi-step process, in which systematic, visual characterization of sediment conditions was performed using SPI to refine the sampling program for the BAZ. Based on analysis of the SPI-generated data (e.g., observation of burrowing, evidence of feeding tubes, redox potential discontinuity), the BAZ was defined as

[27] Refer to Appendix C.
[28] Each composite included a series of aliquots collected at mid ebb tide (ebb tide composite) or mid flood tide (flood tide composite) during each semi-diurnal tide for a 2-week period.

6 cm in UBC, and 10 cm in MBC, BCC, and LBC. Sediment sampling for COPCs was then performed in both the BAZ and at selected depth intervals in 1-m (3.3-ft) cores. A broad suite of COPC analyses (i.e., target compound list/target analyte list [TAL]) and conventional parameters was employed in most sediment sampling locations. Additionally, a focused scope of sampling for polychlorinated dibenzo-*p*-dioxins and dibenzofurans (i.e., dioxins/furans) was performed, consisting of 10 mudflat locations per study segment. Sample locations were distributed to achieve representative spatial coverage across waterway morphologic features (i.e., mudflats, subtidal channels, deep subtidal channels, and tributaries). Additionally, an initial characterization of surface (0–5 cm) and subsurface (10–15 cm) marsh sediment was performed along transects throughout the BCSA tidal areas.

- The Phase 1 biota assessment program included an aquatic community assessment and an analysis of COPC concentrations in mummichog, white perch, and blue crab. This sampling was conducted to support the evaluation of exposure to higher trophic-level receptors (both human and ecological). The biota sampling program emphasized mummichog due to their relatively small and well-defined home range, and use of waterway and marsh habitats, supporting a means to characterize both the magnitude and gradients of biouptake of COPCs in relation to data from co-located surface water and sediment samples.

- Final screening of the candidate reference sites was completed in Phase 1 and included field collection of salinity data from each site. Bellman's Creek, Mill Creek, and Woodbridge River were selected as RI reference sites (Figure 1-1). These sites were selected based on a consideration of a variety of physical (e.g., geology, land use, watershed size), chemical (e.g., salinity), and biological (e.g., vegetation) factors similar to those in the BCSA. Richmond Creek was removed from consideration given its significantly higher salinity levels compared to the BCSA. The reference site selection criteria used were based on EPA guidance for reference site identification under Superfund (USEPA 1994, 1997, 2002) and were detailed in the RI/FS work plan.[29] After final selection, initial multimedia COPC characterization was performed.

A Phase 1 Site Characterization Report was submitted to EPA on February 26, 2010. EPA provided comments on the Phase 1 Report (June 2010), and these comments were addressed through a Response to Comments Memorandum (July 2011). Appendix A includes a summary of comments received related to project documents, and identifies relevant sections of the RI Report that address previous Agency questions or comments.

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[29] Refer to Appendix C.

3.3 Phase 2 (2010-2011)

Fieldwork associated with Phase 2 was conducted in 2010 and 2011. The Phase 2 RI tasks included characterization of COPC concentrations in biota tissue, and more detailed characterization of horizontal and vertical distribution of COPCs in UBC, MBC, LBC, BCC and Above Tide Gate Areas in waterway and marsh sediment. In addition, factors influencing mercury methylation/demethylation and COPC fate and transport were evaluated. The Phase 1 hydrodynamic and sediment transport measurements were continued and additional data and analyses of sediment deposition and resuspension dynamics were completed, including SEDflume and near-bed particle dynamics analyses. In addition, data on hydrodynamics, sediment transport, and surface water COPC concentration were collected during Hurricane Irene. Biological characterizations included characterization of the species composition of the aquatic and marsh communities and of trophic linkages in the aquatic food web, and a functions and values assessment of the marsh vegetation/habitat. A summary of all samples collected in Phase 2 is provided in Table 1 of Appendix C.

The following overview identifies the primary tasks/objectives of the Phase 2 sampling programs:

- The hydrodynamics task included continuation of the hydrodynamic/water quality data collection from Phase 1, with supplemental collection of transect data, total suspended solids (TSS) characterization, and upland freshwater flow and sediment load measurements. A dye study was completed to measure residence time and exchange between tidal reaches and with the Hackensack River. Monitoring of near-sediment-bed flow velocities and sediment deposition/resuspension dynamics was conducted at several locations. Sediment samples were analyzed using SEDflume techniques to assess stability.

- Routine surface water sampling for COPCs and water quality parameters was continued from Phase 1. Samples were also collected in marsh tributaries and pools to evaluate marsh-waterway exchange of COPCs and particulates. Whole water samples were filtered using different size filters to evaluate COPCs and TSS. Storm sampling was completed to evaluate COPC concentrations during precipitation and tidal surge events.

- The sediment sampling program included characterization of vertical and horizontal COPC distribution in marsh sediment, supplemental BAZ sample collection and coring in the waterways, and shallow surface sediment (hereafter termed thin BAZ [2 cm]) sample collection for correlation with tissue COPC concentrations. The thin BAZ increment samples were added, in part, to evaluate relationships between the aquatic community and sediment. In addition, high-resolution cores (2-cm sample increment) were collected in waterways to evaluate vertical COPC profiles and sediment deposition history using geochronological markers.

- Marsh interflow discharge was evaluated through the installation, sampling, and water level monitoring of shallow wells within the root zone of the *Phragmites* marsh sediment, and samples of interflow seepage were collected along the marsh banks.

- The biota investigation focused on further characterization of waterway and marsh communities. An additional fish community survey was completed, and characterization of the food web using stable isotopes was undertaken. A waterway benthic macroinvertebrate survey also was completed. Samples were collected for measurement of COPCs in fish. The marsh invertebrate and insect communities were assessed, and the marsh BAZ was evaluated in 2-cm increments through the top 6 cm of marsh sediment. COPC samples were also collected to assess concentrations in marsh invertebrates and *Phragmites* tissue. A study of marsh functions, values, and primary production was completed. Finally, mercury air monitoring and human use camera surveys were conducted to support the human health risk assessment.

The Phase 2 Site Characterization Report was submitted to EPA on September 28, 2012. EPA provided comments on the Phase 2 Report (June 2013). These comments were addressed through a Response to Comments Memorandum (December 2013). Appendix A includes a summary of comments received related to project documents, and identifies relevant sections of the RI Report that address previous Agency questions or comments.

3.4 Phase 3 (2012–2015)

Fieldwork associated with Phase 3 was conducted from 2012 through 2015 in accordance with a series of work plan addenda and the QAPP.[30] The overall objective of the Phase 3 investigations was to refine chemical characterization of all media, with a focus on understanding COPC transport and fate (with consideration of the effects of Hurricane Irene on August 27–28, 2011, Tropical Storm Lee on September 6–8, 2011, and Hurricane Sandy on October 29–30, 2012), and factors controlling COPC bioavailability and biouptake. In addition, a number of tasks were completed to support the risk assessments. A summary of all samples collected in Phase 3 is provided in Table 1 of Appendix C.

The following overview identifies the primary tasks/objectives of the Phase 3 sampling programs:

- Additional characterization of flow and sediment loading was conducted in the East and West Riser ditches, and the Rutherford Ditch. Flow monitoring and sediment texture analysis was also completed in UPIC. Further measurements of suspended sediments and organic matter were collected to support development of the sediment transport model. Tide gauge monitoring

[30] Refer to Appendix C.

was conducted for several years at two locations in BCC and UBC to evaluate the range of water levels over daily tidal cycles and under varying climatic conditions.

- Extensive monitoring programs were implemented in 2014 and 2015 to assess surface water COPC and organic matter exchange between the waterway sediment bed and surface water and between waterways and marshes, using optical monitoring equipment and extensive discrete sample collection. The contribution of marsh interflow and surface exchange processes to surface water COPC concentrations was also evaluated.

- The sediment sampling program focused on assessment of sediment stability and deposition patterns. Additional high-resolution sediment cores were collected in waterways and marshes to measure vertical COPC concentration patterns and geochronology. Extensive sediment probing was completed throughout the waterways to characterize the thickness of soft sediments. In addition, COPC concentrations in recently deposited sediment were characterized. Mercury partitioning in both waterway and marsh sediments was measured using sequential extraction and other measures. COPC concentrations in porewater in mudflat and marsh sediments were measured using several methods. Detailed characterization of sediment redox was performed through a sediment voltammetry survey.

- The Phase 3 biota assessment focused on developing a robust data set to support the risk assessments. This included characterization of the aquatic community and food web using stable isotopes, gut content analysis, and age classification; measurement of COPCs in a range of aquatic species, including white perch of several size classes; marsh invertebrate COPC measurements; marsh and waterway benthic invertebrate community characterization; waterway sediment toxicity testing; dioxin/furan and PCB congener characterization; and marsh vegetation community surveys. Supplemental mercury air monitoring and human use camera surveys were also conducted to support the human health risk assessment.

The results of Phase 3 investigative work from 2012 to 2014 have been previously reviewed with EPA in annual meetings. Findings from Phase 3 have been incorporated with the results from the scoping activities, Phase 1, and Phase 2 work, and a detailed integrated analysis is presented in this RI Report.

3.5 Baseline Monitoring

A baseline monitoring program (BMP) was developed to document pre-remedial (i.e., baseline) conditions in the BCSA, as well as to establish the core elements and methods for long-term monitoring of the study area. The data collected under this program supplement the RI data, and will be used along with other data collected during longer-term (post-remedy) monitoring to assess temporal trends within the BCSA in response to remedial actions or other changes in the system.

A BMP Work Plan was submitted to EPA (May 2011, rev. August 2011) and periodically updated.[31]

Overall, the BMP is focused on collecting chemistry data for COPCs in tissue and surface water, as these data are important to both assessing risk under the baseline condition and evaluating the effectiveness of remedies that are targeted at reducing COPC accumulation in biota. Specifically, the following types of samples are collected:

- Biota: composite sampling of mummichog (whole body) and white perch (fillet) at 40 locations in the BCSA and 20 stations total in the Bellman's Creek and Mill Creek reference sites. Tissue samples are analyzed for mercury, methyl mercury, and PCBs.

- Surface water: automated monitoring at 4 locations in the BCSA, and manual water sampling in proximity to the BCSA biota sampling locations. Unfiltered surface water samples are analyzed for mercury, PCBs, and TAL metals.

Chemistry data in these media are expected to be variable due to temporal and/or species-specific considerations, and the additional data from the BMP will help characterize the variability that is inherent in each media prior to remedy implementation. The BMP focuses on summer sample collection as this is a period of higher biological activity, which increases the potential for biouptake. Additional surface water samples have been collected in the fall in several years for comparison of cooler weather conditions to warm weather conditions.

3.6 Pilot Studies

As described in the EPA-approved Pilot Studies Work Plan (BCSA Group 2012b), the pilot studies program is evaluating thin-layer sand and amendment addition technologies in mudflat and marsh settings of the BCSA. Because the pilot study test plots represent an alteration of the baseline conditions at the site, pilot study data are generally not incorporated in RI data analyses. However, some limited data generated from the pilot studies have been considered. Specifically, sediment COPC data from untreated (control) plots in mudflats and marshes have been included in the RI data set as these data represent baseline conditions. In addition, samples of recently deposited sediment were collected from treated mudflat plots in Phase 3, and those data are considered as they are from similar sample increments as the thin BAZ samples and are relevant to understanding sediment transport and the characteristics of recently deposited sediment. In addition, monitoring of redox conditions in relation to tidal inundation/saturation and other factors in the test and control plots supplemented other RI data in developing an understanding of mercury and methyl mercury biogeochemical dynamics.

[31] Refer to Appendix C.

SECTION 4

ENVIRONMENTAL SETTING

The following presents a summary of the environmental setting of the BCSA, including the historical events that shaped the present day conditions at the site, and the physical, chemical, and biological templates that frame the present ecological habitats and human uses at the site.

4.1 Historical Setting

The current physical, chemical, and biological setting of the BCSA has been shaped by natural events such as glaciation, sea level rise, and storm events, as well as anthropogenic activities such as land development (residential, commercial and industrial), hydrologic modifications, wetland filling, and waste management practices. Figure 4-1 summarizes several of the key natural events and anthropogenic activities that have shaped the BCSA, which are described below. Appendix B provides a detailed chronology of these events/activities.

The formation of the Hackensack River basin began with a large lake trapped behind glaciers in the region. The lake-bottom beds are the predominant sedimentary deposits that cover the bedrock in the Meadowlands and throughout the BCSA, most notably the varved clay deposit that is laterally extensive throughout the BCSA (Stone et al. 2002). Warming of the globe starting approximately 15,000 years ago led to breaches in the glacial lake and the formation of the Hackensack Valley. Our present geologic time period is called the Holocene Epoch, which started with global warming and glacial retreat approximately 12,000 years ago. The base morphology of the Hackensack River basin present today was established at this time. As temperatures began to steadily rise in the Holocene, the human population began to increase and initiate significant change to land and waterway uses in the area.

Prior to significant human settlement, vegetation in the BCSA was a mixture of black ash swamp and grassland primarily supported by local watershed and Hackensack River freshwater flows. Up to the recent millennia, the system slowly evolved to an Atlantic white cedar swamp, an almost exclusively freshwater system. The BCSA was essentially a freshwater creek with a wetland riparian zone that fed into the Hackensack River until major anthropogenic changes began in the 17th century. Up to then, the system was very likely in a dynamic equilibrium with seasonal upland runoff and river flows. The system was effectively isolated from brackish tidal waters and it is unlikely that the system supported significant sediment accumulation during most of the Holocene prior to human settlement.

Settlement of the BCSA and surrounding area by Europeans resulted in many irreversible changes to the watershed. Beginning in the 17th century, the Atlantic white cedar forest was cut and burned extensively. Trenches dug to mark property boundaries and to drain land for mosquito control, agriculture, and development significantly altered the local hydrology. However, maps in the 19^{th} century still show the BCSA area as containing a significant cedar swamp.

The largest recent change in the system resulted from the construction of the Oradell Dam in 1902. The dam substantially reduced freshwater from the upper Hackensack River watershed into the estuary. The dam construction was closely followed by the construction of the East and West Riser tide gates in the northern end of the BCSA watershed and the dredging of BCC in 1911, which created a deep straight channel directly connecting MBC and UBC with the Hackensack River and essentially bypassing LBC. Combined with the dredging of the Hackensack River in the lower portion of the estuary, the major anthropogenic changes in the early 20^{th} century facilitated encroachment of brackish water into the estuary and caused major habitat transitions driven by salinity increases in both the estuary and the BCSA. Within approximately 20 years of completion of the Oradell Dam, cattails, wild rice, and other freshwater wetlands plants were replaced by the common reed *Phragmites* (USFWS 2005; Hackensack Riverkeeper 2008). Essentially the BCSA was transformed from a freshwater wetland to a brackish saltwater marsh and had taken on the characteristics of a typical fringing salt marsh dominated by estuarine tidal flow and sediment delivery. The most significant sediment accumulation since the beginning of the Holocene likely began during the late 19^{th} and early 20^{th} centuries due to these changes.

The range of salinity brought about by these anthropogenic changes also has had a significant effect on the aquatic community, as aquatic species diversity is typically lowest between 5 to 10 ppt (Barnes 1989). In this range, few freshwater species can tolerate the increasing salinity, but the salinity is still too low to support marine species. The foregoing habitat factors (physical/chemical conditions, disturbance, and recent succession dynamics) were altered by human activity and amplified by increasing sea level over the last 200 years. In addition, the position of Oradell Dam at the head of the tide is a barrier to migratory fish that were once abundant in the Hackensack River estuary (Kiviat and MacDonald 2002; Hackensack Riverkeeper 2012).

Through the first half of the 20^{th} century, land development within the BCSA was largely constrained to the upland perimeter along established roadways. Development and landfilling activities in the latter part of the 20^{th} century resulted in extensive filling of wetlands in the BCSA (approximately 63 percent reduction during the 20^{th} century). The resulting net loss of marsh and waterways caused a significant reduction in the tidal prism and altered stormwater inputs to Berry's Creek. Further, with the development came chemical inputs to the system from the full range of land uses. Sources of chemical stressors to the BCSA, including industrial discharges, landfills, and other unpermitted discharges, all had a significant impact on water and sediment quality in the BCSA, and are discussed in Section 6.1.

Waste disposal practices, particularly sewage discharges to the BCSA and the Meadowlands in general, had detrimental effects on surface water dissolved oxygen concentrations and the aquatic community throughout the 20th century. Due to sewage discharges, dissolved oxygen in the BCSA was below the NJDEP regulatory threshold of 4 parts per million (ppm) much of the time from approximately the 1930s to the early 1990s, particularly in UBC and MBC during the ebb tide. Other sewage-associated parameters, such as ammonia and fecal coliform, were also elevated above toxic levels and remain elevated in the system today.[32] Diversion of sewage out of the BCSA to the Hackensack River has resulted in measurable improvements in dissolved oxygen throughout the system, although dissolved oxygen concentrations below 4 ppm are periodically observed (Section 4.7.4). The previously observed pattern of lowest dissolved oxygen concentrations during ebb tide is now reversed, with lower dissolved oxygen concentrations typically observed at high tide rather than low tide, and lower dissolved oxygen levels in the lower reaches (LBC and BCC) compared to the upper reaches (MBC and UBC).[33] This suggests that influx of water from the Hackensack River, which exhibits elevated biological and chemical oxygen demand from ongoing discharges by publicly owned treatment works (POTWs) and combined sewer overflows (CSOs) to the river, significantly contributes to the depressed dissolved oxygen concentrations in the BCSA. POTW discharges to the Hackensack River also continue to contribute elevated levels of other sewage-associated parameters to the estuary, including the BCSA.

In summary, the BCSA has undergone a series of changes at multiple scales that established the current interrelationships of the physical, chemical, and biological templates. Many of these conditions are typical of urban ecosystems and must be taken into account in future planning and management of these environmental resources (Odum and Barrett 2005; USEPA 2008b; Niemelä et al. 2011).

4.2 Current Land Use

As regional populations increased, early industrial development took place throughout the Meadowlands communities. These industries primarily consisted of heavy manufacturing, storage tank farms, and chemical processing facilities. By the late 1960s, this pattern of heavy industrial use began to move toward lighter uses such as assembly and light manufacturing and more warehousing and distribution. Though some heavy industry remains in parts of the Meadowlands District, the dominant industry in the BCSA is manufacturing, with a total of 14,892 businesses listed in the North American Industry Classification System (NJMC 2004).

Land use in the BCSA watershed north of Paterson Plank Road is dominated by Teterboro Airport (Figure 1-2). The area immediately surrounding Teterboro Airport is fully developed with light industrial operations, except for areas occupied by wooded wetlands and marshes. This area is

[32] Refer to Sections 3.3 and 3.4 of Appendix E.
[33] Refer to Section 3.2 of Appendix E.

framed by the East and West Riser ditches (Figure 1-2), which are nontidal tributaries to Berry's Creek. Prior to 1930, these features were initially installed and pumped to drain the wetlands formerly present in this area as part of land reclamation efforts for the Borough of Teterboro (NJDOH 1930). Presently these tributaries represent the primary sources of freshwater flow to the BCSA tidal zone, draining 59 percent of the BCSA uplands watershed to UBC.

The most dominant development in the central portion of the BCSA (between Paterson Plank Road and Route 3) is the New Jersey Sports and Exposition Authority (NJSEA) Complex located in East Rutherford. Construction of the complex began in the early 1970s and was completed in phases by the early 1980s. The complex was redeveloped in 2009, including construction of a new rail crossing south of Paterson Plank Road at the north end of Walden Swamp and Ackerman's Marsh (Figure 1-2). This work involved placement of piers and filling for the rail bed in the waterway and marshes. Redevelopment/construction activities at the NJSEA facility included construction of a new stadium and the Xanadu complex (which was subsequently sold, renamed to the American Dream Meadowlands, and planned for further redevelopment, as described in Section 4.3) with the addition of impervious surfaces and associated runoff. The NJSEA complex is bounded to the west by Walden Swamp, which separates it from Berry's Creek, except at the southwestern point near Route 3 where the stormwater management basins discharge to the creek. Commercial and light industrial properties are present to the west of Berry's Creek, adjacent to Route 17. The BCSA extends to the northwest across Route 17 into a predominantly residential portion of Rutherford.

With the exception of some industrial, commercial, and limited residential land use to the west, the southern portion of the BCSA (south of Route 3) is occupied by undeveloped *Phragmites* marshes. Formerly, significant portions of this area were operated as unregulated solid waste dumps into the 1970s, including the Lyndhurst and Rutherford landfills. A portion of this area was previously slated for development under a joint agreement between NJMC and EnCap Golf Holdings; however, the development plans were abandoned in 2008 and have been replaced by the Kingsland Development Plan (NJMC 2011, Section 4.3). Two new residential developments were recently completed adjacent to LBC, including a 2014 development on the western bank of LBC and a 2015 development on the northeastern edge of Tollgate Marsh. Both of these developments were completed in areas of previously filled wetland.

4.3 Potential Future Management and Development Activities

Natural and anthropogenic changes to the system will occur in the future. Natural changes include the response of the system to climate change and sea level rise. Anthropogenic changes can include, but are not limited to, development and redevelopment consistent with zoning and development regulations; regional flood control with diking, pumping, tide gates and storm tide gates; channel filling and straightening; armored crossings (i.e., bridge abutments); stormwater management, including routing and concentration of flow; sewage and combined sewer management on the Hackensack River; and upstream reservoir management for flows and sediment loads. Depending on scale, scope, implementation, and timing of these changes, they could affect the fate, transport, and bioavailability of COPCs during the BCSA remedy.

Hurricane Sandy caused major damage to infrastructure throughout the coastal areas in New Jersey and New York, although without much noticeable impact on the BCSA waterways and marshes. In response to those impacts, several studies were conducted on improving flood protection and coastal community resilience. Commissioned by Rebuild by Design (An Initiative of the President's Hurricane Sandy Rebuilding Taskforce), the "New Meadowlands" project report (Rebuild by Design 2014) put forth an integrated vision for protecting, connecting, and growing the Meadowlands as part of a larger regional analysis (metropolitan area of New York) that mapped a maximal spectrum of risks to a comprehensive set of vulnerabilities, combining flood risk with social vulnerability, vital network vulnerability, pollution risk, and other considerations. The authors note that wherever this risk profile is greatest, "federal investments in protection make most sense" and identified "the Meadowlands area as an urgent priority" (Rebuild by Design 2014). The report includes identification of three pilot study areas in the Meadowlands. Pilot Study Area 1 (Little Ferry, Moonachie, and Carlstadt) includes a large portion of the BCSA.

The development of the "New Meadowlands" concept plan led to $150 million of starter money going from the U.S. Department of Housing and Urban Development to NJDEP to plan, design and construct flood and storm surge protection measures in and around the BCSA (HUD 2014). Such measures, if constructed, would likely alter the hydrodynamics and sediment transport and deposition dynamics in a large portion of the BCSA. To ensure the potential for adverse effects on the BCSA remedy are minimized, NJDEP, EPA, and the BCSA Group are meeting and exchanging information as the respective alternatives analyses go forward.

Other major anthropogenic modifications are not planned for the tidal portion of the BCSA. There will be periodic repairs and replacements of tide gates, in particular the UPIC tide gate in UBC. A turnpike widening project crossing BCC is under construction with only localized activity along the edge of the canal near the Hackensack River. The construction of the rail crossing over the northern portion of MBC during the RI has caused only localized effects on the sediment bed. West Riser and Rutherford tide gate replacements and modifications did not result in apparent changes in sediment bed or COPC distribution in those areas. In addition, the Fish Creek culvert under the landfill access road in LBC may require repair or replacement in the near future.

In the upland area surrounding the tidal area of the BCSA, most of the land is zoned non-residential with residential development concentrated above the 100-year flood zone. The upland is more than 90 percent developed and land use is not likely to change substantially within a 30-year planning horizon. A revision of the 2004 master plan for the Meadowlands is expected in the next few years as the legislation that merged the NJMC and the NJSEA called for an update to the master plan.

The most substantial pending development/redevelopment projects near but outside of the BCSA are:

- The American Dream Meadowlands project consists of a $3.7 billion dollar shopping and entertainment complex in East Rutherford. The project area and all planned activities are outside of the tidal area, and stormwater management is already in place for areas in the BCSA. As a result, this project is not likely to have any noticeable impacts on the BCSA.

- The Kingsland Redevelopment Plan (NJMC 2011) encompasses approximately 1,400 acres, much of which falls within the LBC. Existing land uses in the redevelopment area include several former landfills, communications transmission towers, public utilities, and the NJSEA office complex. Land uses in the surrounding area consist of office, commercial, industrial, communications transmission towers, and residential. The purpose of the Kingsland Redevelopment Plan is to facilitate the environmental closure of landfills to reduce adverse environmental impacts resulting from potential exposure to contaminated soil, and to reduce the adverse effects of leachate on water quality and landfill gas emissions on air quality. Redevelopment of this area is not likely to impact the BCSA tidal area because of the runoff management and groundwater leachate controls that are included in the long-term plan for these properties.

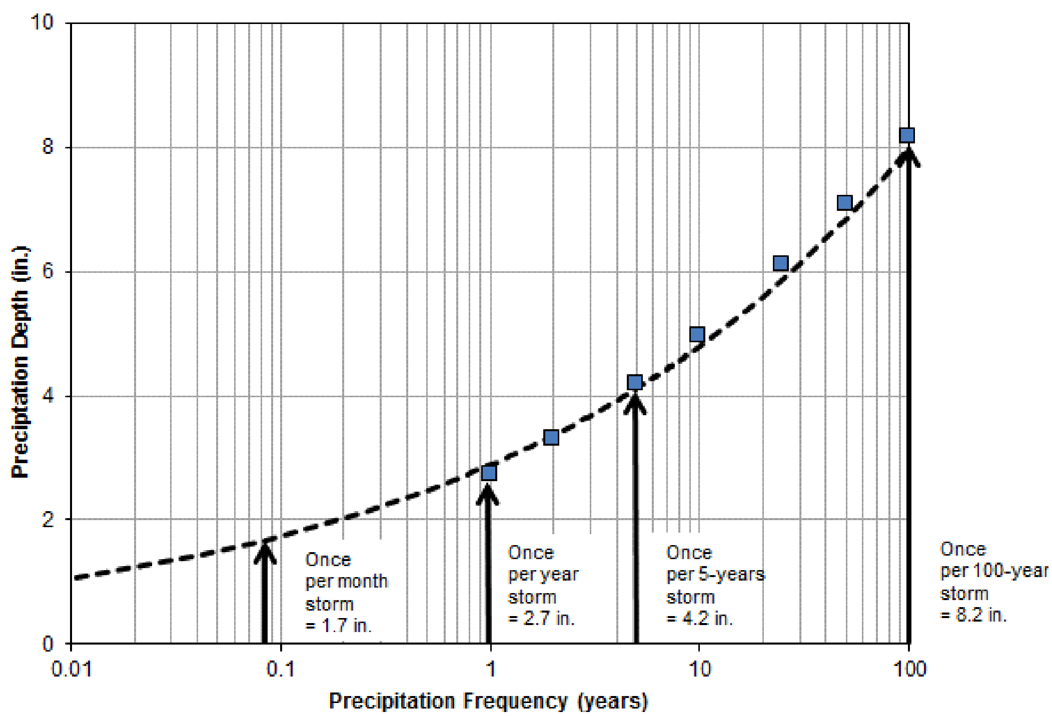
4.4 Cultural Resources

A Stage IA cultural study was conducted to assess the potential for significant historical and archaeological resources within the tidal zone of the BCSA (BCSA Group 2010). The Stage IA cultural resources investigation was completed in accordance with Section 106 of the National Historic Preservation Act, as amended; the Secretary of the Interior's Standards and Guidelines for Archaeology and Historic Preservation (Federal Register, Volume 48, No. 190); and the archaeological survey and reporting guidelines of the New Jersey Historic Preservation Office.

Most of the area evaluated was determined to have a low potential for significant archaeological resources due to extensive areas of ground disturbance caused by modern construction projects, landfills, and other development. No registered prehistoric archaeological sites were identified. A limited number of historic properties and sites, such as the Canadian Car and Foundry Company site, the former Erie Railroad, and the 1930s Route 3 Bridge over Berry's Creek were identified. Once the remedial strategies are defined, appropriately qualified professionals will review them in relation to the known historical properties and areas of archaeological sensitivity. The need for further investigation, such as a Stage IB archaeological survey, will be evaluated during the FS remedial alternatives analysis and remedy selection for the site once potential project impacts are known.

4.5 Climate

As is discussed in Section 2.2 of Appendix D, the BCSA watershed is located within the Central New Jersey climate zone, which experiences a moderate climate influenced by seasonal variations, proximity to the Atlantic Ocean, and localized warming due to the urban heat island effect (Office of the State Climatologist 2015). Air temperature ranges from over 90 degrees Fahrenheit during summer months to below freezing during the winter. Average annual precipitation is 46 in. The area receives a fairly uniform amount of precipitation throughout the year, ranging, on average, from a low of 2.5 in. in February to a high of 4.5 in. in September. Measurable rainfall is recorded within the BCSA at Teterboro Airport once every 3 days, on average. The majority of these rainfall events produce amounts of precipitation that are 1 in. or less and, in turn, relatively small amounts of storm runoff. The annual (once per year) storm magnitude is 2.7 in. over a 24-hour period (Graphic 2). Higher-volume storms are less frequent, with storms totaling greater than 4 in. of rainfall over 24 hours occurring less than once every 5 years.



Source: Bonnin et al. (2006)

Graphic 2. Rainfall Return Frequency

Heavy precipitation events recorded in New Jersey have increased over the past two decades, occurring twice as often as in the previous century (Broccoli et al. 2013). Although total precipitation recorded each year from 2009 to 2015, the period encompassing RI monitoring, generally matched long-term patterns[34], four storm events totaling greater than 4 in. of rainfall over 24 hours have occurred in the region in the past 5 years. The total annual rainfall in 2011 was the second greatest measured in the entire period of record available (1869 through 2015).[35] A total of 69 in. of precipitation was recorded at Teterboro Airport in 2011, which is 23 in. greater than the annual average. Further, 13.9 of the 69 total inches of rainfall fell during just 2 storms (Hurricane Irene and Tropical Storm Lee; see below). Air temperatures are also increasing, with 9 out of 10 of the warmest calendar years on record occurring since 1990, and the warmest year in the 118-year period of record occurring in 2012. Increased temperatures are a significant stressor in urban areas and increase the effects of other stressors, such as low dissolved oxygen.

Situated along the eastern seaboard, the BCSA is subject to influences of hurricanes, tropical storms, and Nor'easters that can result in heavy precipitation and/or large storm surges. Generally, these storms are rare, and only 5 of the 10 largest storm precipitation events in the last 118 years were associated with a named tropical storm or hurricane.[36] Two of the largest single day rain events occurred in August of 2011 during Hurricane Irene and Tropical Storm Lee. Hurricane Irene was a rare storm event that produced 8.2 in. of rainfall in 24 hours, which is equivalent to a once in 100 year storm magnitude. The hurricane also delivered an approximate 0.9-m (3-ft) surge above the normal tide, reaching a combined peak height of 1.85 m (6.07 ft) mean sea level (MSL; Figure 4-2). Low-lying upland areas were flooded in the larger Hackensack River estuary, including the BCSA, due to the combination of the very large volume of stormwater runoff and the increased tide elevations during the storm. Tropical Storm Lee impacted the area approximately 1 week after Hurricane Irene, delivering a total of 5.7 in. of rainfall and associated storm runoff to the area.

Hurricane ("Superstorm") Sandy impacted the New York/New Jersey area in October 2012. Unlike Hurricane Irene, Sandy's impact was principally related to the extreme tidal surge associated with the storm. Sandy produced minimal precipitation (<0.2 in. total) in the BCSA; however, the tidal surge during Hurricane Sandy was 2.8 m (9.2 ft), reaching a peak tidal amplitude of 3.5 m (11.48 ft) MSL (Figure 4-2). Sandy resulted in extensive flooding throughout coastal areas of New Jersey and New York, with peak flood levels exceeding the 500-year flood elevation in the BCSA. Peak water levels during the surge exceeded the elevation of much of the land area between the BCSA and the Hackensack River, resulting in flooding of a large percentage of upland areas of the BCSA due primarily to the surge of water moving into the estuary.

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[34] Refer to Appendix D.
[35] Based on the New York Central Park observation station records from 1869 to 2015.
[36] Refer to Appendix B.

4.6 Relative Sea Level Rise

Sea level sets the template for a large number of the physical, chemical, and biological conditions of estuaries, and the morphology of a tidal marsh is inherently related to MSL. The semi-diurnal tide in the BCSA oscillates around MSL over a range of approximately 1.8 m (5.8 ft) between mean higher high and mean lower low tides (Figure 4-2).[37] Tidal flows are primarily responsible for the delivery and distribution of sediments in the estuary and the BCSA.

In a tidal marsh, increasing water levels due to sea level rise will increase the depth in the waterways that link to the marshes. Water levels in the marshes also increase. An increase in cross-sectional areas and water depth will decrease the velocities in the waterways. The decreased velocities reduce the shear stress at the sediment bed and create conditions conducive to sediment deposition. Morris et al. (2002) and Kirwan and Guntenspergen (2010) have shown that in a system with adequate sediment supply on the Atlantic Coast, the rates of elevation gain in a typical salt marsh exceed water level increases due to sea level rise.

Relative global sea level is estimated to be increasing by 1.7 mm/year, on average (IPCC 2013). Sea level along the New Jersey coast reportedly is increasing faster than the global average, at approximately 3 to 4 mm/year (Cooper et al. 2005; Miller et al. 2013), and is likely to continue at similar or greater rates.(Miller et al. 2013; Titus et al. 2009). Recent sediment measured accretion rates in the BCSA tidal zone marshes average 6.8 mm/year (MERI 2015), suggesting that the marshes are keeping up with sea level rise at this time.[38]

4.7 Physical Setting

The BCSA is a typical fringing tidal marsh within the Hackensack River estuary, with large expanses of intertidal areas that are undergoing long-term sedimentation. Estuarine environments, such as the BCSA, are where fresh water from the uplands mixes with saline marine water. Like most estuaries in the United States, the Hackensack River estuary evolved from a drowned river valley as a result of sea level rise following glacial melting after the last ice age. Sea level rise since the last ice age has caused the ocean to encroach into the river mouths creating the estuarine mixing zone. Anthropogenic modification dating back to European settlement of the region has hastened the advance of more saline water into the estuary (Section 4.1). During estuary

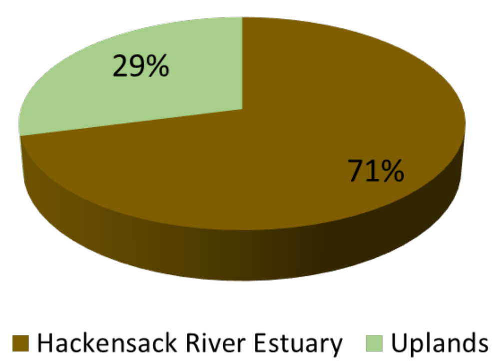
[37] The tides in the BCSA are mixed semi-diurnal; meaning that two tides flow into and out of the system each tidal day (24.84 hours), with different high and low tide elevations on each tide. Mean higher high water is the average of the highest high water levels during each tidal day over the period of record. Mean lower low water is the average of the lowest low water levels during each tidal day over the period of record.

[38] Sediment accretion rates measured using SETs do not account for the influences of compaction and digenesis and are thus generally higher than sediment deposition rates estimated using geochronological markers. As is discussed in Section 6.5.1, the average deposition rate for the BCSA marshes is ~0.4 cm/year based on ^{137}Cs profiles.

development, fringing wetlands form as sediment from the uplands and ocean fill in the shallow intertidal regions (Dyer 1998; Prandle 2009).

Tidal water from the Hackensack River estuary flows into and out of the BCSA twice daily. Tidal flows are dominant (Graphic 1) and the estuary is the primary source of sediments deposited within the BCSA (Graphic 3).[39] Within the BCSA, tidal flows interact with the limited freshwater baseflow, as well as episodic storm runoff draining from the urban watershed.

The *Phragmites* marshes are a dominant feature of the BCSA, occupying more than 74 percent of the tidal area. The physical structure of the *Phragmites* marshes creates a broadly stable landscape that supports consistent deposition of sediment carried into the marshes during routine tidal flooding. Estuarine marshes are among the most productive ecosystems in the world (Bruland 2008), and organic matter derived from the *Phragmites* marshes influences overall ecosystem function as well as COPC fate and transport.



Graphic 3. Estimated Sources of Inorganic Sediment to the BCSA Based on Monitoring from 2009 through 2011[40]

4.7.1 Morphology

The morphology (i.e., geometry) of the BCSA tidal zone (Figure 4-3, Table 4-1) is a manifestation of the long- and short-term transport and accumulation of sediment in the BCSA. The principal morphologic features of the BCSA include:

- **Main Channel**—The main channel or primary waterway refers to the tidal channel that runs generally south to north from the confluence of the BCSA with the Hackensack River. This

[39] Refer to Section 3 of Appendix G.
[40] Refer to Section 3 of Appendix G.

channel is the principal conveyance of tidal water and estuarine sediment into and out of the BCSA, and for stormwater flow through the BCSA tidal zone. The main channel consists of subtidal channel areas and intertidal mudflats. The subtidal channel areas are the deepest sections of the waterway through which the majority of the flow is conveyed, and thus are subject to the largest range and highest peak velocities. Deep subtidal channel areas (operationally defined as <-3.0 m [<-9.8 ft] MSL depth) occur primarily at meander bends in the main channel of UBC, upper MBC, and LBC; and along the thalweg of lower MBC and BCC. Intertidal mudflats (Graphic 4) present at the margins of much of the main channel are above mean lower low water elevation (-0.78 m [-2.55 ft] MSL; Figure 4-1) and are thus subject to routine flooding and drainage with the semi-diurnal tides. These shallow water regions of the main channel are subject to lower peak flow velocities than the adjacent, deeper subtidal channels areas.

Graphic 4. Typical Main Channel Mudflat in the BCSA

- **Tributaries**—Tributaries are secondary channels to the main channel. The tributaries are predominantly intertidal, with the exception of the Above Tide Gate Areas, and consist of natural or man-made channels that serve as the conveyances of water and sediment from the waterways to the marshes. Tributaries are shallow and generally low energy/velocity regions relative to the main channel, although several of the BCSA tributaries also convey stormwater flows from upland discharge points to the BCSA main channel, and are thus subject to episodic periods of higher velocity.

- **Marsh—**The BCSA main channel and tributaries are surrounded by more than 306 hectares (~756 acres) of tidal marshes.[41] The broad marshes are densely populated by *Phragmites,* which slows the movement of water and stabilizes the sediment with its dense and deep root structure. The physical structure of the *Phragmites* marshes creates a broadly stable landscape and results in consistent deposition of sediment delivered to the marshes during routine tidal flooding. Small but distinct marsh pools occur scattered across the marshes and are sometimes directly connected to waterway via small tributaries.

Table 4-1. Morphologic Areas (Acres) by Reach in the BCSA

Reach	Deep Subtidal Channel	Subtidal Channel	Mudflat	Tributary	Marsh	Undefined[b]
Above Tide Gate	0	0	0	0.8	2	103
Above Tide Gate – UPIC	0	0	0	4	28	0
UBC	0.4	8	12	25	77	0
MBC [a]	10	23	10	44	201	0
BCC	16	14	9	9	69	0
LBC	2	25	28	68	379	28
BCSA-Wide	29	69	59	151	756	131

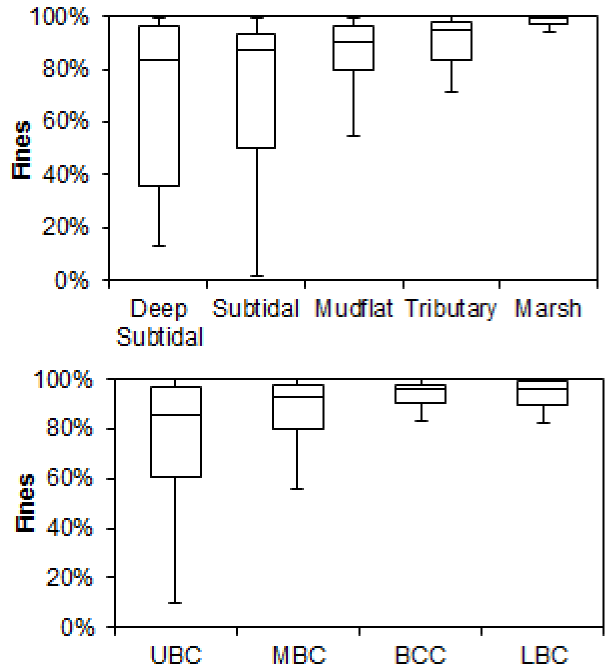
Note:
[a] Includes marsh and tributary areas outside of MBC, west of Ackerman's Marsh (Figure 4-2).
[b] Includes areas outside of the tidal zone, such as the East and West Riser ditches, Rutherford ditches, and upland roads in LBC, that do not have an assigned morphology.

In the typical transport pattern in a wetland, inorganic sediment is conveyed from estuarine and upland sources through the channels and is deposited onto the mudflat and marsh surfaces during flooding tides (Leonard and Reed 2002). The standard morphologic features are maintained in the channels by the constant bi-directional tidal current. Depositional features, such as the extensive mudflats on inside channel bends where the current velocity is lower, and deeper pools with steeper sides on the outer channel bends, are typical of sinuous channel flow such as in the BCSA (Figure 4-3). The presence of these morphologic features in the BCSA suggests that the system is a stable landscape that is maintaining long-term morphology.

Energy in the waterway is typically highest in deep subtidal channels, and then generally decreases from subtidal channel, intertidal mudflat, to intertidal tributary.[42] The lowest energy setting is in the marshes. Although sediments in the BCSA are predominantly fine grained (silts, clays), coarse-grained particles are observed in increasing frequency in morphologic regions with higher energy

[41] Includes the BCSA tidal zone and UPIC.
[42] Refer to Section 2 of Appendix G.

regimes (deep subtidal and subtidal channels, tributaries that convey storm flows) and in some parts of the upper reaches of the BCSA, where a majority of the freshwater flow enters the tidal zone (Graphic 5).



Graphic 5. Distribution of Fine Size Sediment (Clays, Silts) by Morphology and Reach

The marshes also influence chemical and biological conditions in the BCSA.[43] The marshes produce a large quantity of organic matter, in the form of living above- and below-ground biomass (leaves, stalks, roots) (Figure 2-1). Senescence of *Phragmites* generates detritus that is entrained in marshes (e.g., in the leaf litter at the surface of the marsh) or exported to waterways as a result of tidal exchange. These processes represent an ongoing source of organic matter to marsh and waterway sediment. The abundance of organic matter in site sediment influences sediment geochemistry and COPC solubility and bioavailability.

4.7.2 Hydrology and Hydrogeology[44]

The nature of sediment and COPC transport dynamics in an estuarine tidal marsh, such as the BCSA, is fundamentally governed by the interplay of tidal and storm flows in the system, except in the Above Tide Gate Areas. The balance of water inputs to the BCSA (i.e., fresh versus tidal)

[43] Refer to Section 2.3 of Appendix H.
[44] See Appendices D (Urban Hydrology), E (Surface Water Characterization), and G (Hydrodynamics and Sediment Transport) for a more complete discussion of the information summarized in this section.

influences water velocities and sediment transport throughout the system and defines its physiochemical structure (e.g., salinity gradients, flooding/draining of intertidal regions and marshes). The temporally and spatially variable interplay of saline and freshwater inputs dictates water, solute, and sediment transport through the system. Tides govern the typical hydrodynamic circulation in the BCSA. While common storm events can influence mixing within the BCSA, monitoring at the site and hydrodynamic modeling suggest that rainfall event magnitudes on the order of once every 3 years (>3.60 in. of rainfall in 24 hours) are necessary to produce freshwater storm flows that result in notable elevation in velocity throughout the BCSA.[45]

4.7.2.1 Water Balance

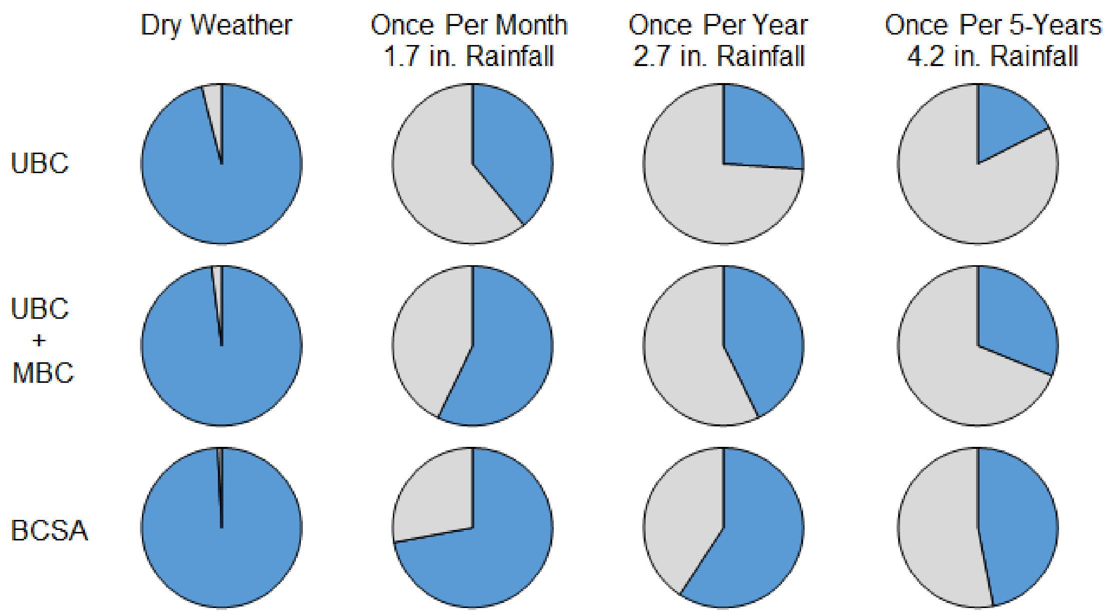
A water balance involves an accounting of water inputs to and removals from the study area. By accounting for the sources (i.e., fresh versus tidal) and quantities of water flowing into and out of various segments of the system, an understanding of the important hydrodynamic mechanisms influencing water flow and sediment transport throughout the system can be achieved. Attachment G2 of Appendix G presents the results for water balance accounting for the 416 hectare (1,029-acre) tidal zone of the BCSA.[46]

The water balance analyses demonstrate that water flow in the BCSA is tidally dominated more than 99 percent of the time (Graphic 6). Freshwater flows (predominantly baseflow[47]) account for less than 1 percent of the total water input in the system under dry weather conditions (Graphic 1). Storm runoff results in short-term increases in the relative proportion of fresh water to tidal water in the BCSA. Because water depth and tidal volume decrease with distance from the Hackensack River and over half of the BCSA uplands drains to UBC, the relative proportion of freshwater to tidal water volume increases with distance from the river.

The relative contribution of freshwater flow to the BCSA water balance notably increases with the increasing magnitude of rainfall events. Flow in the BCSA as a whole is tidally dominated during most storm events (e.g., storms with 24-hour precipitation totals of ≤1.7 in., which occur on average once per month). These common storm events can have a more pronounced influence on UBC and result in storm runoff volumes that are comparable to or greater than tidal volumes in UBC (Graphic 6), nearly complete exchange of tidal water in UBC, and increased mixing of water

[45] Refer to Section 3 of Appendix G and Section 4.3 of Appendix E.
[46] For the purposes of the water balance analysis, the tidal zone area was defined based on the BCSA Stormwater Management Model. These model tidal zone areas (1,035 acres) are slightly greater than the tidal zone areas defined by the BCSA reach boundaries. This does not result in a significant effect on the water balance analysis.
[47] Baseflow is freshwater flow in upland drainage channels that is unrelated to stormwater runoff and that discharges to the BCSA tidal zone on a relatively continuous basis. Baseflow is maintained by groundwater inputs and nonregulated discharges.

with downstream reaches. Large magnitude storm events (e.g., once every 1 to 5 years)[48] are necessary to generate a total freshwater volume that approaches or is greater than the tidal prism for the full BCSA (Graphic 6). These large storm events, however, can also be accompanied by tidal surges that result in short-term increases in water levels and tidal flow in the BCSA. While surge events result in increased sediment loading from the estuary to the BCSA, monitoring indicates that surges typically do not significantly increase channel velocities in the BCSA waterways.[49]



Graphic 6. Relative Proportion of Tidal Flow Volume (Blue) to Freshwater Volume (Gray) across the BCSA under Dry Weather and Various Rainfall Magnitudes[50]

4.7.2.2 Surface Water Hydrodynamics

Extensive monitoring and modeling of the flow conditions in the BCSA verify that the BCSA is tidally dominated the vast majority of the time. Consequently, water, solute, and sediment transport within the system are principally driven by tidal processes.[51] Tidal water is exchanged from the Hackensack River to the BCSA at the main channel confluences in BCC and LBC. The majority

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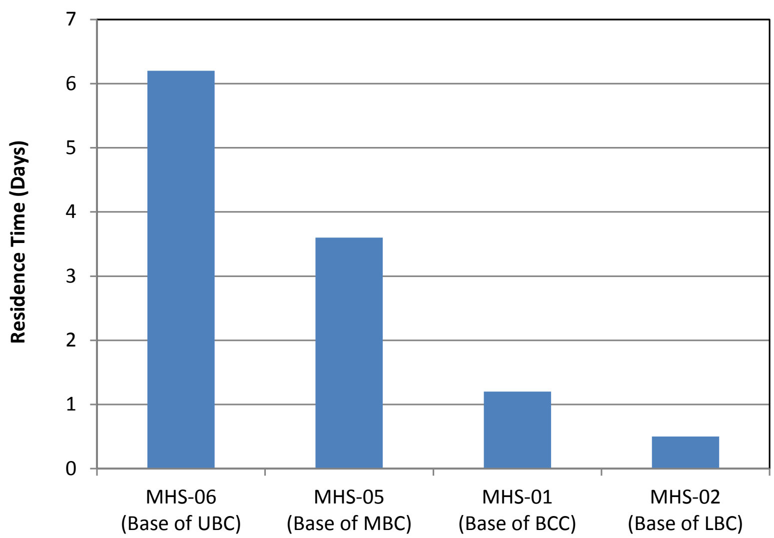
[48] The once per year (2.7 in. in 24 hours) event is estimated to produce a storm runoff volume approximately equivalent to the average neap tidal prism. The once per 5 year (4.2 in. in 24 hours) event is estimated to produce a storm runoff volume approximately equivalent to the average spring tidal prism.
[49] Refer to Section 2 of Appendix G.
[50] Calculations compare the average single tidal prism to the total freshwater flow, which includes baseflow total and the total storm runoff volume estimated for each rainfall amount using a site-specific Stormwater Management Model (refer to Appendices D and G).
[51] Refer to Appendix G.

of tidal flow to MBC and UBC is conveyed through BCC, where the main channel is considerably deeper than it is in LBC (Figure 4-3). The lower and middle reaches of MBC are a tidal mixing region between the less-circulated UBC and the frequently exchanged BCC. Multiple lines of evidence, such as the dye study and hydrodynamic modeling, show that there is limited exchange of water from UBC/MBC/BCC with LBC.[52]

Water residence time[53] increases with distance from the river (Graphic 7). Typical residence times in LBC and BCC are approximately 1 day or less, reflecting the direct connection of these reaches to the Hackensack River and the twice-daily tidal flow of water. UBC and MBC, by contrast, are characterized by residence times of 3 to 6 days. Storm flows associated with rainfall events result in increased downstream movement of water from UBC and upper MBC into the lower reaches, and thus there are shorter residence times during these events. However, large storm events (e.g., once every 1 to 5 years)[54] are necessary to flush water from UBC through BCC in a single day.



Graphic 7. Average Residence Time of Surface Water in the BCSA

Tidal velocities in the waterways are a function of the size of the tidal prism (i.e., the upstream volume of water exchanged by a single tide). Channel velocities at any given location generally increase with the size of the tidal prism upstream of that location. The tidal prism decreases with

[52] Refer to Section 2 of Appendix G.
[53] Water residence time is the time required to replace a defined volume of water in a system (e.g., the volume of water in the BCSA or a given reach of BCSA) with a new water volume.
[54] The once per year (2.7 in. in 24 hours) event is estimated to produce a storm runoff volume approximately equivalent to the average neap tidal prism. The once per 5 year (4.2 in. in 24 hours) event is estimated to produce a storm runoff volume approximately equivalent to the average spring tidal prism.

distance from the Hackensack River, as the total upstream area that is tidally flooded decreases. As a result, the highest waterway tidal velocities tend to be in BCC and the lowest velocities in UBC, a finding that has been verified both by empirical measurements and hydrodynamic modeling of the system.[55]

Episodic storm events result in increased freshwater flows from the uplands[56], and localized elevated waterway velocities at the entry points of the storm flows.[57] The size of the storm event governs the magnitude and extent of the elevated velocities. Because the largest proportion of the upland flow enters the BCSA tidal zone in UBC[58], storm flows from relatively routine rainfall events (e.g., rainfall totals that occur more than once per year) are concentrated in UBC and the northern portions of MBC. As such, waterway velocities are generally only elevated in UBC and MBC.[59] Rainfall events that occur less frequently (less than once per year) can elevate waterway velocities farther down the system. Monitoring at the site and hydrodynamic modeling suggest that rainfall event magnitudes on the order of once every 3 years (>3.6 in. of rainfall in 24 hours) are necessary to result in notable elevation in velocity throughout the BCSA. The variations in velocity as a result of changing tidal and climatic conditions can affect sediment transport in the system (Section 4.7.3).

4.7.2.3 Marsh Interflow

The near-surface horizon (i.e., approximately the top 3 ft) of the *Phragmites* marshes is characterized by a highly dense root structure. Qualitative estimates based on field observations of marsh cores suggest that roots comprise a large percentage of the subsurface volume in this zone—creating secondary porosity and supporting freer vertical and horizontal movement of water than would otherwise be expected based on the fine-grained silt and clay particle size of the marsh sediment.[60] Lateral drainage of interstitial marsh porewater from the *Phragmites* marsh root zone that is exposed along bank faces of portions of the waterways is visually evident in the BCSA during low tide periods. This interflow drainage is primarily driven by tidal flooding of the marshes and bank infiltration during high tide, although precipitation-based recharge also contributes to interflow.

The greatest degree of marsh flooding occurs during spring tides[61], when water levels at high tide are typically above the elevation of the marsh plain (Figure 4-2). Limited portions of marsh can

[55] Refer to Section 2 of Appendix G.
[56] Refer to Appendix D.
[57] Refer to Section 2.5 of Appendix G.
[58] Refer to Attachment G2 Figures 4a–e of Appendix G.
[59] Refer to Section 2.5 of Appendix G.
[60] Refer to Section 5.2 of Appendix E.
[61] Refer to Attachment G2 of Appendix G.

also be engaged during neap tides—primarily in near-tributary areas. Monitoring of shallow (screened at depths of 15–30 cm and 30–60 cm) wells in the BCSA marshes has demonstrated that this water flow is limited to the very near surface of the marsh sediment (typically less than the upper 30 cm of the marsh sediment thickness) and discharges to adjacent tidal tributaries and waterways of the BCSA.[62] Flow and drainage from marsh surface sediment is limited by small head differentials over long distances, and the estimated total volume of interflow discharge over a single tidal cycle is very small relative to the BCSA tidal prism (0.00002 to 0.2 percent).[63]

4.7.2.4 Hydrogeology

The Hackensack River basin is located within a section of the Piedmont physiologic province of the Appalachian Highlands that was influenced by glaciation (Carswell 1976). Bedrock underlying the region consists of sedimentary sandstone and mudstone of the Passaic Formation (Carswell 1976; Drake Jr. et al. 1997; Exponent 2004), at depths of approximately 60 m (200 ft) below ground surface in the BCSA (Carswell 1976). The predominant deposits that cover the bedrock in the Meadowlands and throughout the BCSA are the glacial lake deposits associated with the former Lake Hackensack, most notably the varved clay deposit that is laterally extensive throughout the majority of the Meadowlands and the BCSA (Stone et al. 2002).

The varved clay is overlain by Holocene materials that are generally described as marsh and estuarine deposits, fill materials, and post-glacial stream terrace deposits in local, higher-elevation areas (Carswell 1976; NJDEP 2008a). The estuarine deposits comprise the "soft sediments" that are present throughout the majority of the waterways of the BCSA.[64] The soft sediment ranges in typical thickness from an average of 0.7 m in UBC to 1.9 m in BCC. However, the thickness is spatially variable: soft sediment may be as much as 3.6 m thick in areas of BCC and LBC, but the varved clay may be exposed locally in deep pools located at meanders in the waterway. The majority of the developed land surrounding the waterways and marshes of the BCSA was created by filling former marsh land.

Groundwater flow occurs in the sandstone and mudstone bedrock of the Passaic Formation, the Pleistocene glacial till deposits underlying the varved clay, and in the unconsolidated Holocene surface deposits (Widmer 1959; Carswell 1976). The Passaic Formation represents the primary groundwater resource in the Meadowlands region (Herman et al. 1998). Bedrock groundwater (Passaic Formation) and groundwater associated with the Pleistocene glacial till deposits are isolated from the surface sediments of the BCSA by the extensive varved clay stratum, which is a

[62] Refer to Section 5.2 of Appendix E.
[63] Refer to Section 5.2 of Appendix E.
[64] Refer to Section 3.2 of Appendix F.

confining unit (Herman et al. 1998). As a result, only water associated with the Holocene surface deposits has the potential to interact with impacted sediments and surface water in the BCSA.[65]

Groundwater associated with fill and native unconsolidated materials that compose the BCSA uplands surface deposits has the potential to discharge to local creeks and tidal marshes of the BCSA. Because these surface deposits are thin and only partially saturated, they have little value as a groundwater resource (Carswell 1976). The highly urbanized character of the BCSA uplands (extensive paved surfaces, curbed and guttered roadways, storm sewers) limits recharge to the uplands surface deposits. This, coupled with the flat topography of the area surrounding the BCSA tidal zone and associated low hydraulic gradient to drive shallow groundwater flow, limits the amount of groundwater discharge to upland creeks or directly to the BCSA tidal zone. The limited groundwater discharge from upland areas is reflected by the low baseflow measured in upland tributaries.[66]

4.7.3 Sediment Transport Dynamics

Emergent marsh wetlands typically act as a sediment trap for estuarine and upland sediments in a drowned river estuary like the Hackensack River estuary. They fill in with sediment over time, especially during periods of sustained sea level rise. Typically, salt marsh systems similar to the BCSA on the Atlantic Coast are morphologically stable systems (Friedrichs and Aubrey 1988).

The summary discussion of sediment transport dynamics presented here is based on a more comprehensive analysis and discussion of the sediment transport CSM presented in Appendix G. It considers multiple lines of evidence, including, but not limited to vertical profiles of COPCs and geochronological markers in high-resolution cores of BCSA sediments, characterization of suspended particulate flux and dynamics in the water column and near the sediment bed, and sediment transport modeling.

4.7.3.1 Sediment Sources

As is typical with a fringing marsh system, the BCSA is net depositional[67], accumulating inorganic and organic sediment brought into the system primarily during tidal exchange with the Hackensack River estuary. Uplands baseflow and runoff also contribute sediment to the system. A large portion of the organic sediment in the system is generated internally through autochthonous (photosynthetic production within the local system) production in the marshes. The majority of the time, flow in the BCSA is dominated by tidal exchange with the Hackensack River estuary (Graphic 1), and the relatively low energy (i.e., velocity) in the system favors deposition of

[65] Refer to Section 2.4 of Appendix D.
[66] Refer to Section 4.1 of Appendix D.
[67] Refer to Appendix F.

sediment coming into the system (Section 4.7.2.2).[68] Figure 2-1 illustrates the general movement of sediment into the system from the uplands and tidal sources. Particulates move into the system and accumulate as they are transported from the higher energy areas of the waterway to the lower energy areas of the waterway and marshes where net sediment accumulation occurs. The long-term sediment accumulation patterns over the past century reflect the constant supply of external sediment from estuarine and upland sources, as well as the influences of disturbances caused by infrequent storm events. Tidal exchange and the associated estuarine sediment supply are greatest near the BCSA tidal inlets at the Hackensack River and decrease with distance upstream. The upper end of the BCSA is characterized by increasing influences of freshwater inflow and associated uplands-derived sediment supply. The dominant mass accumulating in the BCSA sediment is inorganic.

The *Phragmites* marshes produce a large quantity of organic matter, in the form of living above- and below-ground biomass (leaves, stalks, roots) (Figure 2-1). Senescence generates a considerable volume of detritus (leaves, stalks) that is retained in marshes (e.g., in the leaf litter at the surface of the marsh) or exported to BCSA waterways due to tidal exchange.[69] The *Phragmites* detritus is composed of both labile (easily decomposed) and refractory (slowly decomposed to inert) organic matter. The labile material is progressively decomposed during transport and when deposited in the surface of the waterways and marshes—creating increasingly smaller size-fraction POC over time. The net accumulation of organic material derived from the marshes and from other sources (e.g., tidal flow from the Hackensack River) in sediment is dominated by the refractory portion which is responsible for approximately 6 percent of the mass accumulated in waterway sediment and 19 percent of the mass accumulating in marsh sediment.[70] In addition to contributing to the accumulation of sediment, the process of autochthonous production and subsequent decomposition of *Phragmites* detritus supplies a large amount of POC to suspended particulates in surface water and, thereby, substantively influences COPC fate and transport and biouptake (Sections 6.2 and 6.3).

4.7.3.2 Short-Term Sediment Transport Processes

Short-term sediment transport processes are primarily driven by routine tidal flow and episodic storm flows.[71] The BCSA waterways experience variable velocities and resultant shear stresses at the sediment bed across the tidal flood and ebb cycle (Graphic 8). Higher velocities occur as tidal water floods into and ebbs out of the system, particularly in the main channels through which the vast majority of tidal flow is conveyed.[72] Velocities decline to near zero as the tide approaches

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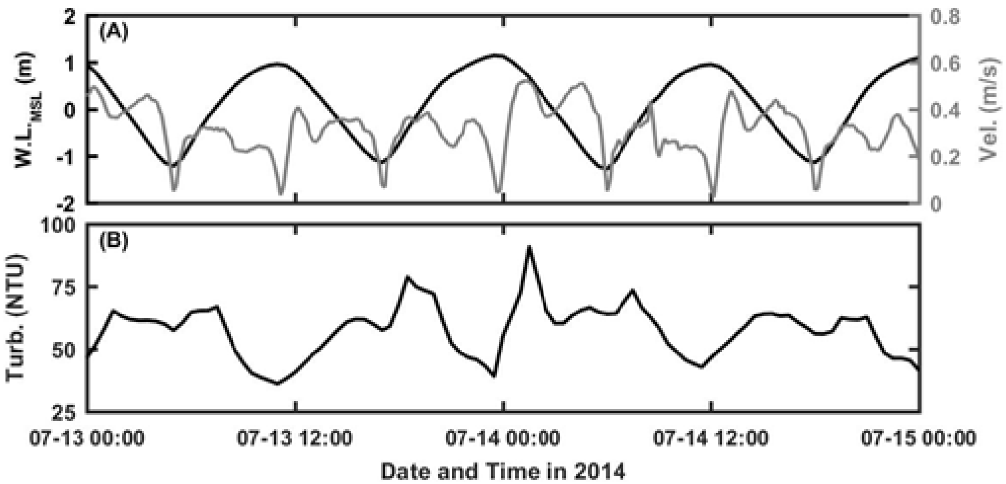
[68] Refer to Section 3.1 of Appendix G.
[69] Refer to Section 2.3 of Appendix H.
[70] Refer to Section 3.2 of Appendix F.
[71] Refer to Section 3.1 of Appendix G.
[72] As shown by empirical measurements and modeling presented in Appendix G.

slack tide phases (Graphic 8). This tidally driven cycle of velocity and shear stress is responsible for short-term sediment transport in the BCSA. Long-term sediment transport processes are discussed in the following section (Section 4.7.3.3).

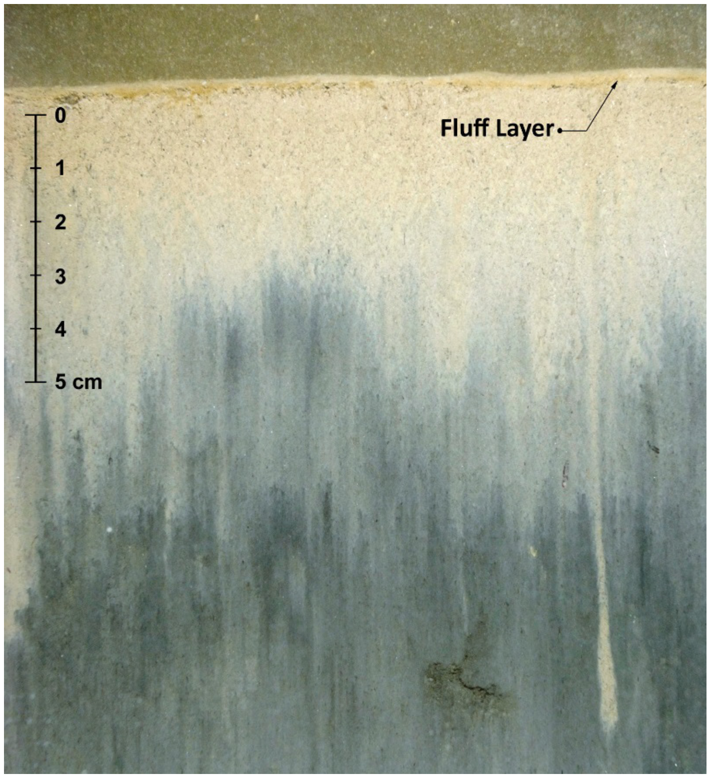


Note: W.L. = water level, Vel. = velocity, Turb. = turbidity.

Graphic 8. Tidal and Velocity (A) and Turbidity (B) Patterns in the Main Channel at Station MHS-05 Located at the Base of MBC

As discussed in Section 4.7.2.1, upland storm runoff events can result in short-term increases in channel velocity in the waterways (predominantly in UBC). Storm surges typically do not substantively influence waterway velocities. The marshes, due to their higher elevation and presence of dense *Phragmites*, do not experience significantly elevated shear stresses even during the very rare, major storm events such as Hurricane Irene.

A common element of estuarine sediment beds is a thin (~0.5 cm) unconsolidated fine sediment layer, often termed the fluff layer (Sanford 1992; Maa and Lee 2002; Small and Prahl 2004), which resides on the surface of the waterway sediment bed (Graphic 9). The fluff layer is composed of inorganic and organic material derived from all sediment sources to the system. Surface water particulates depositing to the waterway sediment surface are a substantial component of the fluff layer. These particulates have, on average, an organic content of 26 percent derived primarily from the large load of organic detritus from the *Phragmites* marshes. Thus, BCSA fluff materials have characteristically low density and are relatively easily suspended from the surface of the waterway sediment bed during peak flood and ebb tide velocities (Graphic 8). During subsequent low-to-zero velocity slack tide periods, particulates in the water column settle, with some particles depositing back to the sediment bed. This is a common process in estuaries and fringing marshes (Sanford 1992; Maa and Lee 2002; Winterwerp and Van Kesteren 2004).



Graphic 9. SPI Showing the Presence of the Fluff Layer on the Surface of the Waterway Sediment Bed

An important component of fluff layer transport is its association with COPCs in waterway surface sediment, as described in Section 6.2. Due to the relatively long residence times of water in the upper reaches (Graphic 7), the fluff material may reside at the sediment surface in regions of the system for multiple days and have the opportunity to sorb COPCs from the surface of the waterway sediment bed. Resuspension from the fluff layer is an important mechanism for the short-term transport of COPCs from the surface of the waterway sediment bed into the water column, where they are available for biouptake (Section 6.3) and can be transported and accumulate in lower-energy regions of the waterways (e.g., mudflats) and marshes.[73]

4.7.3.3 Long-Term Sediment Transport Processes

The BCSA supports long term net deposition of sediment throughout the majority of the BCSA, as is demonstrated by multiple lines of evidence (e.g., profiles of COPCs and geochronological

[73] Refer to Section 3.1 of Appendix G and Section 5 of Appendix E.

markers in high-resolution cores, surface elevation tables (SETs), sediment transport modeling).[74] An estimated 2,700 metric tons of the inorganic sediment mass that enters the BCSA from estuarine and upland sources is retained within the BCSA tidal zone each year.[75]

Episodic upland storm events influence sediment transport dynamics in the BCSA through increased delivery of uplands-derived sediment to the BCSA and short-term elevation of flow velocities in waterways. Common storms (i.e., storm magnitudes that occur an average of once per month) do not result in substantial elevation of waterway channel velocities or resuspension of bedded sediment beneath the thin (~0.5 cm) unconsolidated fluff layer.[76] However, less frequent, larger storm events can cause short-term elevation of TSS due to additional input of sediment and localized resuspension of particulates from the waterway sediment bed.[77] Model predictions and other lines of evidence (e.g., high-resolution cores, estimates of TSS flux during storm events) indicate that the waterway sediment bed responds with local erosion in areas where flows are focused and shear stresses are elevated (e.g., subtidal areas and tributaries that convey storm flows).[78]

Generally, magnitude of erosion is low (typically <3 cm based on model predictions)[79] and is primarily limited to subtidal channel areas and meander bends in the main channel. Rare, major events, such as Hurricane Irene and Hurricane Sandy (which have return frequencies of once in 100 to 500 years, respectively), can result in deeper erosion. Within the level of uncertainty inherent in these type surveys, bathymetric change analyses of the BCSA waterways based on surveys[80] completed in 2008 and 2014 (which includes the two hurricanes) shows minimal to no measurable change (<30 cm) across the large majority (about 91 percent) of the BCSA main channel and measureable (>30 cm) shoaling in approximately 3 percent of the main channel area.[81] The bathymetric analysis suggests measurable (>30 cm) deepening (net erosion) in several geographically separate areas—typically along portions of the subtidal channel and at meander bends. These areas comprise approximately 6 percent of the main channel area and were primarily in UBC and LBC, where the analysis is based on single-beam surveys and is least certain.[80]

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[74] Refer to Section 3.4 of Appendix G and Section 3.2 and Attachment F1 of Appendix F.
[75] Refer to Section 3.2 of Appendix G.
[76] Refer to Section 3 of Appendix G.
[77] Refer to Section 4.3 of Appendix E.
[78] Refer to Section 3 of Appendix G and Section 4.3 of Appendix E.
[79] Refer to Section 3.4 of Appendix G.
[80] Multi-beam surveys were completed in BCC and MBC. Due to the shallow water and vessel access limitations, single-beam surveys were completed in LBC and UBC as a series of cross channel transects spaced at ~100 ft. Because the single-beam surveys require extrapolation between transects, the bathymetric change analyses for UBC and LBC are more uncertain than the areas surveyed by multi-beam.
[81] Refer to Figure 3-7 of Appendix G.

Vertical profiles of geochronological markers and COPC concentrations in waterway sediment high-resolution cores show variable degrees of sediment accumulation, as influenced by morphology, proximity to upland discharges, and proximity to sediment supplies.[82] High-resolution cores exhibit a range of deposition rates generally between approximately 0.75 and 2.0 cm/year in most channel, mudflat, and tributary morphologies.[83] Additionally, mercury and PCB depth profiles in waterway high-resolution cores are predominantly indicative of ongoing depositional processes. The majority (~75 percent) of waterway sediment cores exhibit natural recovery from historical maximum COPC concentrations at depth (Section 6.5). Exceptions occur in localized areas, such as areas adjacent to major upland discharges where sediment accumulation appears limited; and in UPIC, where sediment deposition rates are lower due to the reduction in sediment supply resulting from the construction of the PIC tide gate.[84] The patterns of variability are consistent with the more dynamic environment of the waterways and the localized reworking of the sediment bed during episodic, large storm flows, followed by enhanced deposition as the system returns to typical conditions.[85]

Deposition of sediment in marshes is controlled by sediment trapping during tidal inundation, accumulation of *Phragmites* detrital mass, and sea level rise. High-resolution cores of marsh sediment show clear evidence for steady deposition in the marshes, with strong cesium-137 (^{137}Cs), mercury, and PCB peaks at similar depths below the marsh surface across the study area. ^{137}Cs data indicate an average sediment deposition rate of 0.4 cm/year in the BCSA marshes (Section 6.5.1) and SET, and marker horizon data collected within the BCSA by MERI (2014) show marsh accretion rates of up to 6.8 mm/year.[86] These rates are generally equal to or exceed the rate of relative sea level rise (3 to 4 mm/year; Section 4.6) (Cooper et al. 2005; Miller et al. 2013). Deposition with no erosion is apparent across the marshes during all modeled conditions[87], consistent with the inherent stability of the marsh sediment. COPC profiles in marsh sediment cores reflect the consistently depositional character of the marshes, with historical peak COPC concentrations occurring at depth and a decrease in concentration towards the surface.

4.7.4 Other Stressors

Stressors other than site-related hazardous substances, such as low dissolved oxygen and elevated ammonia and pathogens, frequently occur throughout the BCSA and appear to be related in part to inputs from the Hackensack River.[88] Hypoxia (deficiency of dissolved oxygen) is common in

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[82] Section 3 and Attachment F1 of Appendix F provide a comprehensive analysis of the vertical profiles of geochronological markers and COPCs in BCSA high-resolution cores.
[83] Refer to Section 3.2.1 of Appendix F.
[84] Refer to Section 3.2.1.3 of Appendix F.
[85] Refer to Appendix G.
[86] Refer to Section 3.2 of Appendix F.
[87] Refer to Section 3.4 of Appendix G.
[88] Section 3 of Appendix E provides more detail on non-CERCLA stressors in the BCSA.

coastal estuaries in close proximity to areas of high population density or developed watersheds that export large quantities of nutrients and organic matter (CENR 2010). Dissolved oxygen concentrations reflect the combined influence of the amount of oxygen-demanding material in the water column and temperature (colder water holds more oxygen than warmer water). Generally, a higher dissolved oxygen level indicates better water quality, and certain minimum levels of dissolved oxygen are needed to support aquatic life.

Overall within the BCSA, the dissolved oxygen concentration is highest in the upper reaches of the system and lowest in reaches closest to the waterway's confluence with the Hackensack River.[89] The overall pattern of increasing dissolved oxygen concentration with distance from the Hackensack River suggests that oxygen-demanding organic material is carried into the BCSA as a result of tidal exchange with the river. Regional sewage discharges and CSOs to the Hackensack River are recognized sources of organic materials and nutrients that result in low dissolved oxygen levels (NYNJHEP 2012).

New Jersey has established a surface water criterion for estuarine waters (SE-2), applicable to the BCSA tidal waters, that dissolved oxygen should not be less than 4 mg/L at any time (NJAC 7:9B-1.14(d)). Dissolved oxygen levels fall below this criterion more than 59 percent of the time across all reaches of the BCSA during the warmer months.[90] During these months, concentrations fall below the criterion even more frequently (70 to 78 percent of the time) at locations closer to the Hackensack River.[91] Further, during these months, dissolved oxygen levels below 2 mg/L, which are considered lethal to aquatic life (NJDEP 2014), occur 13 percent of the time in all BCSA reaches and up to 15 percent of the time near the confluence with the Hackensack River.

Ammonia is a common pollutant in urban estuaries and is potentially toxic to aquatic species (Eddy 2005); control of ammonia is a focus of a total maximum daily load evaluation for the New York/New Jersey Harbor estuary (HydroQual 2012). Ammonia is typically attributable to four main sources: 1) as a component of historical and current sewage treatment plant and CSO discharges, 2) runoff from lawn fertilizers, 3) atmospheric deposition, and 4) via ammonification, a process by which fungi and heterotrophic bacteria mineralize organic nitrogen in detritus, thereby generating ammonia in sediment and surface water (Henry and Heinke 1989). All surface water ammonia concentrations measured in the BCSA during the RI were higher than the New Jersey Surface Water Quality Standard of 0.03 mg/L. However, this criterion is only applicable to free (nonionized) ammonia (NH_3), the concentration of which is estimated to be below 0.03 mg/L in most BCSA surface water samples at ambient conditions.[92] The highest ammonia levels in surface

[89] Refer to Section 3.2 of Appendix E.
[90] June through September.
[91] Refer to Appendix E.
[92] Approximately 1 percent of total ammonia will be present in nonionized form at ambient conditions (USEPA 2013).

water are consistently found in BCC and LBC[93], which may stem from sewage-derived ammonia associated with the Hackensack River. Surface water ammonia concentrations are not correlated to sediment ammonia concentrations, indicating that BCSA sediment is not the primary or major source of ammonia observed in the water column.[94]

Fecal coliform is a pathogen that is commonly present in urban settings and introduced via sewage discharges and runoff that are affected by anthropogenic and animal wastes (Henry and Heinke 1989). Fecal coliform was analyzed in samples collected throughout the BCSA in the four quarterly Phase 1 sampling events in 2009–2010 and was found to be ubiquitous in the BCSA.[95] The prevalence of fecal coliform limits the usability and aesthetic aspects of the BCSA for human populations. Colony counts exceeded the New Jersey Surface Water Quality Standard of 770 colonies/100 mL in approximately one-third of all the samples from the BCSA, with higher counts during warmer conditions. There is no clear spatial trend in the coliform data in the BCSA site.

4.8 Ecosystem of the BCSA and Hackensack River Estuary

The BCSA and the larger surrounding New Jersey Meadowlands are part of an urban landscape shaped by a history of human use, development, and change. Habitat loss, resource extraction, altered hydrology, urban runoff, industrial discharges, landfill and sewage discharge, nutrient inputs, and eutrophication have had a cumulative effect of creating the habitats and character of the Meadowlands ecosystem as it exists today.

The current wetlands of the Meadowlands have changed in extent and character from pre-development conditions, and the remaining wetlands have changed considerably in response to changes in salinity, hydrology, and urbanization (Section 4.1).[96] Filling and alterations to hydrology also changed the periodicity and duration of inundation for the remaining wetlands. The range of tidal and nontidal habitat types, their complex interspersion, and the occurrence of many large blocks of habitat contribute to the importance of the Meadowlands region to wildlife (Kiviat and MacDonald 2002b). The estuarine wetlands are extensively fragmented by roads and other rights-of-way, which can adversely affect the distribution of certain species (USFWS 2007).

Anthropogenic changes, in conjunction with sea level rise, have led to the decline of freshwater wetland communities and the rapid expansion of brackish and salt marsh communities throughout the Meadowlands (Kiviat and MacDonald 2002a). These changes have facilitated not only the spread of *Phragmites* throughout the BCSA and the broader Meadowlands region, but have also

[93] Refer to Section 3.3 of Appendix E.
[94] Refer to Section 3.3 of Appendix E.
[95] Refer to Section 3.4 of Appendix E.
[96] Refer to Appendix B.

caused a shift in the aquatic community of Berry's Creek to brackish water species tolerant of the higher salinity (NJMC 2004).

The extensive urbanization of the region also resulted in increased discharge of pollutants from both point and nonpoint sources (Section 4.1). These discharges contribute to water quality impacts (e.g., low dissolved oxygen) that influence the biological community. These cumulative effects of urbanization are a key determinant of the composition and character of the ecological communities of the BCSA and broader Meadowlands region.

Urbanization results in changes to the overall composition and character of the ecology of receiving waters (Meyer et al. 2005; Walsh et al. 2005; Roy and Kennan 2008). Aquatic ecosystems in urban areas are most often characterized by reduced biotic richness associated with the presence and/or dominance of more stress-tolerant species. Fish community and benthic community diversity declines as sensitive species are replaced by species that are more tolerant of pollution and other impacts of urbanization. In addition, there is an overall change in ecosystem processes, such as nutrient uptake and organic matter retention (Feminella and Walsh 2005; Walsh et al. 2005). In the Meadowlands, these changes have been linked to the decline in the region's fisheries (Bragin et al. 2005) and have been identified as a primary determinant of the composition and character of its benthic community (Bragin et al. 2009).

4.8.1 Regional Habitats and Communities

Tidal and nontidal marshes and associated waterways are the principal habitats of the Meadowlands region. Brackish (mesohaline and oligohaline) marshes are the predominant wetlands in the middle reaches of the estuary, where the BCSA is located. There is a total of 306 hectares (756 acres) of brackish marsh in the BCSA, and 713 hectares (1,760 acres) of this habitat type in the Meadowlands, making it the largest mesohaline marsh complex in northern New Jersey (HMDC 1984 in Kiviat and MacDonald 2002b). *Phragmites* dominates the plant communities of the brackish marshes in this region, but remnant stands of narrowleaf cattail (*Typha angustifolia*, now rare), big cordgrass (*Spartina cynosuroides*), and Olney three-square (*Schoenoplectus americanus*) are found in some areas (Kiviat and MacDonald 2002b).

Phragmites forms nearly monotypic stands by creating conditions in which other species cannot compete. The height of *Phragmites* vegetation, stem density, and detrital accumulation combine to reduce light and air temperatures at the marsh surface, which, in turn, inhibits the germination or establishment of other plant species. These combined conditions also influence decomposition rates; algal productivity; and habitat conditions for some invertebrates, birds, and fish (Benoit and Askins 1999; Warren et al. 2001; Able and Hagan 2003; Levin et al. 2006).

The marshes of the Meadowlands provide many important wetland functions. More than 265 species of birds use the area, and the Meadowlands is recognized as a major link along the Atlantic

Flyway for migratory species (especially shorebirds) and an important overwintering area for a variety of waterfowl (USFWS 2007). Approximately 40 percent of the migratory bird species that occur in the eastern United States use the Meadowlands as a stopover to feed and rest during the spring and fall migrations (USFWS 2007).

Waterway-associated birds occurring in the region include a variety of shorebirds, wading birds, waterfowl, and gulls. Invertivorous shorebirds, such as the spotted sandpiper (*Actitis macularius)*, are commonly observed using the Meadowlands waterways for foraging and breeding, except during winter (approximately November to March) when they are rarely, if ever, observed (Mizrahi et al. 2007; Reed et al. 2013; NJSEA 2015). Piscivorous and invertivorous wading birds, such as the great blue heron (*Ardea herodias*) and black-crowned night heron (*Nycticorax nycticorax)*, respectively, are well-documented inhabitants of the BCSA and the Meadowlands. Great blue heron, though not known to breed within the Meadowlands, use the area year-round for foraging. Black-crowned night heron are present in the Meadowlands and historically were reported to breed in the area (NJMC 2012), but more recent reports have found no evidence of current nesting activity (NJSEA 2015). Insectivorous passerines, such as the red-winged blackbird (*Agelaius phoeniceus*) and marsh wren (*Cistothorus palustris*), are common in the Meadowlands marshes in all seasons except winter and are known to use the habitat for foraging and breeding (Mizrahi et al. 2007).

The marshes of the region also serve as an important food source for the detritus-based food web of the New York/New Jersey Harbor estuary ecosystem (USFWS 2007). Reed stands are capable of producing large quantities of organic matter. Much of this organic matter accumulates *in situ* as litter beneath the stand, but some portion is exported to the surrounding waterways. Limited research indicates that *Phragmites* detritus is as good or better than saltmarsh cordgrass detritus as food for major detritus-feeding tidal marsh animals (e.g., fiddler crab, grass shrimp, and mummichog), and that these animals do not consistently select one plant community over the other in laboratory experiments (Weis 2000; Weis and Weis 2000).

Epiphytic invertebrates (i.e., those living on the surface of plants) are an important component of the overall marsh community within the region. Grossmueller (2001) sampled macroinvertebrates in the above-ground vegetation and in leaf litter in tidal and nontidal Carlstadt-Moonachie marshes and identified 60 orders or families associated with the vegetation. This included five spider families, one taxon of Opiliones (harvestman), one mite family, one isopod, and one mollusk (slug). Also represented were diverse taxa of insects, especially Aphididae (aphids), Miridae (plant bugs), Cicadellidae (leafhoppers), and Platygasteridae (a family of parasitic wasps). Thirty-seven taxa of invertebrates were identified in the litter, including Nematoda, Oligochaeta, Enchytraeidae, Lumbriculidae, Gastropoda (slug), spiders, seven genera or species of Acarina (mites), Isopoda (pill bugs), Diplopoda (millipedes), Chilopoda (centipedes), and insects. Mites and Collembola (springtails) were the most abundant taxa. These taxa are all surface dwelling organisms (detritus or standing vegetation) and do not burrow into marsh sediments.

The fish community in the Meadowlands wetlands is composed of species adapted to the range of salinity conditions found in the tidal estuarine and freshwater wetlands and includes both resident and migrant (transient) species. An extensive fish survey and species inventory was conducted during a 2-year study from 2001 to 2003 and found 39 species (Bragin et al. 2005). Mummichog (*Fundulus heteroclitus*) was the most abundant species in the survey. Large numbers of white perch (*Morone americana*), Atlantic silverside (*Menidia menidia*), gizzard shad (*Dorosoma cepedianum*), striped killifish (*Fundulus majalis*), and striped bass (*Morone saxatilis*) also were collected. Compared to the findings of a similar survey conducted in 1987 through 1988, there was a general increase in the evenness of the fish community composition and an increase in more desirable game species in the more recent survey, partly attributed to improvements in water temperature and dissolved oxygen levels (Bragin et al. 2005). Mummichog represented 85 percent of the catch in the earlier survey, but 40 percent in the more recent survey. This decrease in mummichog abundance was accompanied by a general increase in other species. White perch represented 28 percent of the catch in the most recent survey, as compared to 1 percent earlier.

Bragin et al. (2009) reported that the benthic community of the Meadowlands is dominated by a few species adapted to the salinity, substrate, and other natural and urban-derived conditions (e.g. high organic matter loading, periods of low oxygen) in the estuary. In a Meadowlands-wide survey, the regional benthic community was dominated by a few organisms. The polychaetes *Hobsonia florida* and *Streblospio benedicti,* and the amphipods *Apocorophium lacustre* and *Gammarus daiberi*, together comprised 74 percent of all individual organisms collected (Bragin et al. 2009). These species are opportunistic and are common in a variety of estuarine and riverine systems, especially those with anthropogenic impacts. When compared to the results of a similar survey conducted in the late 1980s, the diversity of the Meadowlands benthic community had increased, but there was still evidence of a system subject to ongoing regional and localized disturbances that has not allowed a more advanced succession stage of benthic community to develop. Given the benthic community composition in the middle and upper reaches of the estuary (near Berry's Creek) in relation to sewage discharges, Bragin et al. (2009) postulated that organic loading and large volumes of freshwater discharged by sewage treatment facilities in these reaches are a probable disturbance that is limiting composition and diversity of the benthic community.

4.8.2 Berry's Creek Habitats and Communities

Waterways (main channel and tributaries) and marshes are the principal habitats within the BCSA tidal zone. Within the waterways, water depth and the area inundated varies depending on the tidal stage. Waterway habitats include subtidal areas that are permanently inundated and intertidal mudflats that are exposed during low tide. At high tide (mean higher high water is 3.29 ft above MSL), waterway habitat covers approximately 115 hectares (285 acres). At low tide (mean lower low water is 2.55 ft below MSL), waterway habitat covers approximately 43 hectares (107 acres). Some portions of the waterway, especially intertidal tributaries and ditches, can become completely dry during low tide. Marshes consist of the intertidal vegetated wetlands that fringe the tidal waterways that are routinely submerged at high tide and exposed at low tide.

4.8.2.1 Marsh Habitats

More than 306 hectares (756 acres) of marsh occupy the BCSA tidal zone. The BCSA marshes are dominated by *Phragmites*, though other species occur in the more saline portions of the study area near the confluence with Hackensack River and at higher elevations along the marsh fringe or in fill areas.

4.8.2.1.1 Vegetative Communities

Kiviat and Graham (2016) identified and mapped 20 distinct habitats within the BCSA tidal zone as part of a land-based habitat survey conducted as part of the RI (Table 4-2). [97] The *Phragmites* marshes varied from highly dominant (nearly monospecific) stands of common reed to more diverse mixtures of common reed and other brackish marsh plants.

The BCSA marsh is characterized by clear patterns of vegetative communities related to both elevation and salinity. Species richness increased with elevation. Tree- and shrub-dominated vegetation occurred in the higher elevation habitats and was observed mostly on fill soils. A salinity gradient was detected in the wetland flora; the less brackish tidal and nontidal marshes were dominated by *Phragmites*, whereas the more saline marshes, in southern Berry's Creek Marsh and southern Oritani Marsh (Figure 1-2), were dominated either by common reed or in more localized areas by native cordgrasses (smooth cordgrass or saltmeadow cordgrass). A portion of Berry's Creek Marsh was also previously planted with cordgrass as part of the former EnCap restoration project (Figure 1-2). The *Phragmites* marshes closest to the Hackensack River and (presumably) the most saline *Phragmites* marshes in the BCSA also were characterized by shorter sparser *Phragmites* with greater species richness than *Phragmites* marshes elsewhere in the study area.

[97] Refer also to Attachment I7 of Appendix I.

Table 4-2. Habitat Types of the BCSA

Mapped Habitat	Marsh									
	Nevertouch	**Eight Day**	**Paterson Plank**	**UPIC**	**Ackerman's**	**Walden**	**Rutherford**	**Tollgate**	**Oritani**	**Berry's Creek**
Brackish Wet Meadow						X				
Fill Shrubland										X
High Salt Marsh									X	
Tidal Creek								X		X
Tidal Mudflat										X
Tidal Pool		X	X			X	X			X
Low Salt Marsh										X
Marsh Pool				X						
Mixed Common Reed									X	X
Phragmites	X	X		X	X	X			X	X
Railroad Edge							X			
Spoil Shrubland									X	
Spoil Wet Meadow									X	
Spoil Woodland									X	
Woodland									X	
Upland Meadow					X		X		X	X
Upland Shrubland	X					X	X			
Waste Ground										X
Wet Meadow			X					X		
Woodland			X	X	X	X	X	X		

Notes: Habitat types observed in the area surveyed. Additional habitat types are potentially present in other parts of the marsh. This table notes the types of habitats present but not the dominant habitat type.

A total of 268 plant species were identified during the recent survey, 56 percent of which were native to New Jersey. In addition to *Phragmites*, several other nonnative species were abundant, including porcelainberry (*Ampelopsis brevipedunculata*), tree-of-heaven (*Ailanthus altissima*), mugwort (*Artemisia vulgaris*), and mile-a-minute vine (*Persicaria perfoliata*).

The plant species assemblages of the BCSA were compared to published information about the floras and assemblages of the New Jersey Meadowlands, Hudson River estuary, and tidal wetlands of other northeastern states. The common reed brackish tidal marshes of the BCSA are similar to those of the Meadowlands in general. Upland fill plant assemblages have not been well documented in the northeastern coastal states, but those in the BCSA appear to be typical, though possibly more species-rich compared to other areas of the Meadowlands and elsewhere.

A wetland assessment conducted as part of the Phase 2 RI (Biohabitats 2010, Appendix L) indicated that productivity of the BCSA marshes is high. Within the BCSA, average standing crop biomass was highest in BCC and UBC marshes (>5,000 g/m^2), and lowest in LBC marshes (<3,300 g/m^2) and similar to that measured in reference sites. Kiviat and Graham (2016) concluded that the BCSA marshes appear to support especially high above-ground biomass even when compared to other *Phragmites* marshes. The above-ground biomass recorded by Biohabitats (2010), when adjusted to remove the estimated weight of standing dead culms, was in the upper end of the reported range for common reed in the eastern states (e.g., Meyerson et al. 2000), evidence of a stable and productive marsh (Kiviat and Graham 2016).

An evaluation of marsh functions and values using the hydrogeomorphic assessment technique developed for the Hackensack Meadowlands (Louis Berger Group 2004) indicated that BCSA and reference area marshes are very similar in their functional capacities (Biohabitats 2010, Appendix L). The *Phragmites* marshes create a physically stable habitat not at risk of erosion. These marshes also maintain tidal elevations, contribute organic flux to the surrounding waterways, and provide habitat for avian and invertebrate communities.

4.8.2.1.2 Marsh Invertebrates

Consistent with the regional literature (Grossmueller 2001), the BCSA marshes support a rich and diverse invertebrate community. The standing marsh vegetation and the thick detrital layer covering the marsh surface both provide habitat for a rich invertebrate community. A total of 92 taxa were identified during a survey of the BCSA marshes during the Phase 2 investigation.[98] Across all sampled marshes in both habitat types, species diversity and taxa richness in BCSA marshes was found to be higher than or similar to that in reference site marshes (paired based on similarity in salinity in the adjacent waterway; Table 4-3).

Across both BCSA and reference site locations, community abundance was dominated by a small number of taxa (Table 4-4), consistent with brackish marsh systems dominated by *Phragmites* (Angradi et al. 2001). Typically, 10 or fewer taxa contributed 80 percent or more of the total abundance in any given location.

[98] Phase 2 Site Characterization Report, Appendix N (BCSA Group 2012a).

Table 4-3. Marsh Invertebrate Community Richness and Diversity by Habitat Type in BCSA and Reference Site Marshes

Reach	Richness			Diversity (H')		
	Overall Reach	Detritus	Standing Vegetation	Overall Reach	Detritus	Standing Vegetation
UBC & Paired Reference Sites						
Eight Day Swamp	8	7	5	1.2	1.2	1.1
Upper Bellman's Creek	6	6	6	1.1	0.8	1.2
Upper Woodbridge River	6	5	5	0.8	0.8	0.8
MBC & Paired Reference Sites						
Walden Swamp	9	8	8	1.3	1.2	1.3
Middle Bellman's Creek	7	7	4	1.0	1.0	1.0
Middle Woodbridge River	5	4	4	1.0	1.0	0.8
LBC & Paired Reference Sites						
Berry's Creek Marsh	8	8	7	1.5	1.3	1.4
Lower Bellman's Creek	7	7	7	1.4	1.3	1.2
Mill Creek	7	7	6	0.7	1.0	0.6
Lower Woodbridge River	6	5	5	1.3	1.2	1.4

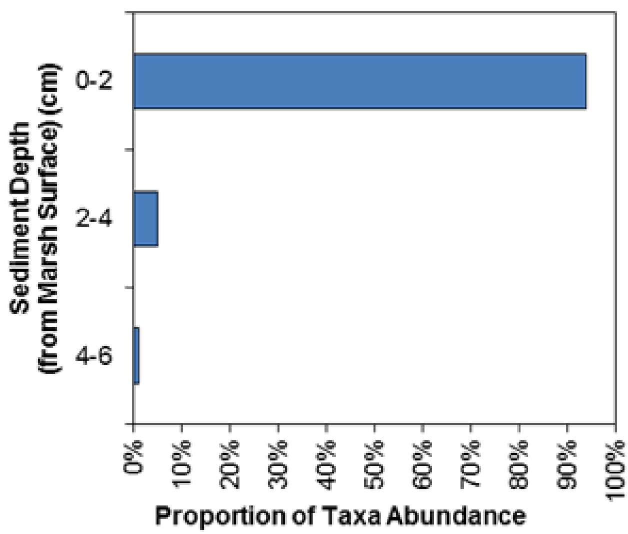
Note: Richness is a diversity index that indicates the number of species present. H' is the Shannon Index and is a calculated metric that takes into account richness and the proportion of individuals of each species. For both metrics, a larger number equates to a greater diversity.

Table 4-4. Percent Abundance for Most Abundant Invertebrate Taxa across BCSA and Reference Site Marshes Based on 2010 Sampling

Common Name	Scientific Name (Family)	BCSA	Bellman's Creek	Mill Creek	Woodbridge River
Ladybug	Coccinellidae	24	9.5	2.6	33
Spider	Various	15	12	6.3	4.6
Marsh fly	Acalyptratae	9.3	34	3.8	18
Parasitic wasp	Chalcidoidea	7.2	7.6	13	1.8
Gall midge	Cecidomyiidae	6.7	8.6	56	--
Shore fly	Ephydridae	5.8	--	--	--
Long-legged fly	Dolichopodidae	5.4	4.1	1.0	4.2
Chironomid	Chironomidae	1.2	1.5	7.1	--
No-see-um	Ceratopogonidae	--	--	1.2	5.2
Planthopper	Delphacidae	--	--	--	14

Notes: Listed taxa are those representing at least 5.0% of total insects collected across the BCSA and across reference sites.
-- = Taxon is not at least 5% present for respective site or reference area.

Of these species, non-burrowing species that occupy the marsh surface predominate. This is consistent with the literature that indicates that most invertebrates in wetlands occur among the litter on the soil surface, where up to 99 percent of individuals and 96 percent of macroinvertebrate production can occur (Gladden and Smock 1990). Sediment cores placed into the marsh surface (below the detrital layer) confirmed that most of the BCSA marsh invertebrate community is distributed above ground rather than within the marsh sediment column. Across all BCSA marshes, few individual organisms were found in marsh sediment and were limited almost exclusively to the top 2 cm of the core (Graphic 10). Further, the vast majority of the organisms found within marsh sediment were the small gastropod (*Littoridinops tenuipes*), a predominantly surface dwelling snail in Meadowlands marshes (Bragin et al. 2009) that does not burrow deep into the sediment.



Graphic 10. Distribution by Depth of Invertebrates in BCSA Marsh Sediment

Given this distribution of invertebrates, and the fact that COPCs are documented to be transported from the waterway to the marsh surface with regular tidal exchange[99], the marsh invertebrates collected from the detrital layer were regarded as good indicators of COPC exposures and uptake within the BCSA marshes for the RI.

4.8.2.2 Waterway Habitats

The oligohaline/mesohaline character of the BCSA has a critical effect on the species that can inhabit the area. Waterways with salinity in the range of that for the BCSA (1 to 10 ppt) typically do not support a diverse community, with decreased species richness along a gradient from high-salinity marine waters to low-salinity waters upstream (Kiviat and MacDonald 2002b).

[99] Refer to Section 5 of Appendix E.

4.8.2.2.1 Fish Community

Prior to the RI, the fish community of BCC was surveyed by the NJMC as part of a larger region-wide fish survey of the Hackensack Meadowlands region (Bragin et al. 2005). During the 2-year survey period (2001 to 2003), a total of 17 fish species were collected from BCC, representing a subset of the 39 species collected throughout the Meadowlands. White perch was the most abundant during the NJMC survey region-wide and represented 66 percent of the total catch in BCC. Other species observed in BCC and their relative abundance are alewife (*Alosa pseudoharengus*), approximately 6 percent of catch; blueback herring (*Alosa aestivalis*), approximately 5 percent of catch; weakfish (*Cynoscion regalis*), approximately 5 percent of catch; and striped bass (*Morone saxatilis*), approximately 4 percent of catch. Mummichog represented only 2 percent of the catch in BCC, which has little of the shallow water habitat preferred by mummichog. Region-wide, mummichog was a dominant fish in the survey and constituted 75 percent of the fish caught in shallow water habitats sampled by seine net.

Two fish community surveys were conducted as part of the RI during 2009 (spring, summer, and fall) and 2010 (summer only). Those surveys indicated that the BCSA fish community is comparable to that of the region and is dominated by mummichog and white perch (Table 4-5). Across both years during the summer season, mummichog and white perch combined to represent 84 percent of the total number of fish caught, comparable to the regional survey findings. Banded killifish (*Fundulus diaphanous*) represented 12 percent of the catch. Other species typically represented less than 0.5 percent of the total catch. Mummichog and white perch were present in all reaches.

Table 4-5. Total Count and Percent Abundance of Fish Species Caught in the BCSA during 2009 and 2010 Summer Community Surveys

Species		BCSA Reach	Count	Percent of Total
Mummichog	*Fundulus heteroclitus*	All	1,111	48
White perch	*Morone americana*	All	827	36
Banded killifish	*Fundulus diaphanus*	All	273	12
Common carp	*Cyprinus carpio*	UBC, MBC, LBC	37	2
Bay anchovy	*Anchoa mitchilli*	All	34	1
Brown bullhead	*Ameiurus nebulosus*	MBC, LBC	8	0.3
Gizzard shad	*Dorosoma cepedianum*	UBC, MBC, LBC	8	0.3
Striped bass	*Morone saxatilis*	BCC, LBC	8	0.3
Atlantic silverside	*Menidia menidia*	UBC, BCC, LBC	6	0.3
American eel	*Anguilla rostrata*	BCC, LBC	3	0.1
Spot	*Leiostomus xanthurus*	UBC	3	0.1
Pumpkinseed	*Lepomis gibbosus*	MBC, BCC	2	0.1
Herring sp.	*Clupeidae*	LBC	1	0.04
Hogchoker	*Trinectes maculatus*	MBC	1	0.04
Menhaden	*Brevoortia tyrannus*	LBC	1	0.04
Sunfish	*Lepomis spp.*	MBC	1	0.04
Weakfish	*Cynoscion regalis*	BCC	1	0.04

4.8.2.2.2 Benthic Community

Similar to the findings by Bragin et al. (2009), the BCSA and reference site benthic community were dominated by a few taxa (Table 4-6). Polychaetes and annelids were the dominant taxa in most reaches and the reference sites. Ostracods (Crustacea) were the only other taxa to represent at least 10 percent of the counts in any given reach. Other Crustacea, bivalves, and gastropods occurred in the BCSA and reference sites but in lower numbers.

Table 4-6. Benthic Taxa Abundance (% of Total Counts) in BCSA Reaches and Reference Sites

Taxa Group	Taxa	UBC (n=30)	MBC (n=16)	BCC (n=6)	LBC (n=3)	Bellman's Creek (n=11)	Mill Creek (n=3)
Annelida	*Limnodrilus hoffmeisteri*	30	2.3	--	--	--	--
Annelida	*Tubificidae* w/o cap setae	26	46	0.1	9.5	92	40
Annelida	*Tubificoides heterochaetus*	7.1	21	39	7.4	0.5	4.9
Bivalvia	*Macoma tenta*	--	0.3	3.6	--	--	--
Crustacea	*Cyathura polita*	2.1	1.4	1.4	0.8	0.1	0.1
Crustacea	*Edotea montosa*	1.6	1.3	0.8	1.0	0.2	0.1
Crustacea	*Leptocheirus plumulosus*	0.1	0.6	1.5	1.3	0.0	0.0
Crustacea	*Ostracoda*	1.3	10	2.1	49	0.2	4.8
Diptera-Chironomidae	*Chironomus sp.*	2.5	--	--	--	0.3	0.1
Diptera-Chironomidae	*Tanypus sp.*	1.8	--	--	--	--	--
Gastropoda	*Hydrobiidae*	2.6	1.6	--	0.4	0.3	--
Polychaeta	*Hobsonia florida*	10	2.1	0.7	1.3	0.9	1.8
Polychaeta	*Laeonereis culveri*	9.6	11	48	25	4.4	45
Polychaeta	*Marenzellaria viridis*	0.4	1.6	1.2	3.4	0.2	0.0
Other organisms	Various	5.0	1.1	0.8	0.9	1.4	3.5

Notes: -- = not found
Taxa with counts equaling 10% or more of total counts

Benthic community composition in the BCSA is generally similar to that observed in reference sites.[100] Across a range of metrics, benthic community composition and characteristics in the BCSA generally overlap with those calculated for the references sites. There is some indication of a shift in community composition moving upstream to downstream within the BCSA, potentially due to differences in sediment habitat related to the salinity gradient that exists in the BCSA and the Bellman's Creek reference site.

[100] Appendix L, Attachment L9 presents a detailed analysis of benthic community composition as part of the sediment quality triad analysis.

4.8.2.3 Wildlife

Although specific wildlife surveys of the waterways were not conducted as part of the RI, observations by field crews as well as BCSA-specific information compiled by Mizrahi et al. (2007) indicate the presence of species common to the region.

Waterway-associated birds observed at the site include a variety of shorebirds—spotted sandpiper, killdeer (*Charadrius vociferous*), and plover species (*Pluvialis* spp.); wading birds—great egret (*Ardea alba*) and snowy egret (*Egretta thula*), great blue heron, black-crowned night heron, yellow-crowned night heron (*Nyctanassa violacea*), and bittern species (*Ixobrychus* spp.); waterfowl—mallard (*Anas platyrhynchos*) and Canada goose (*Branta canadensis*); cormorant (*Phalacrocorax* spp.); and a variety of gulls. These species were observed resting and foraging in the waterways and were observed throughout the length of the study area. The most common picivorous wading bird observed was great blue heron. Spotted sandpipers were commonly observed foraging on the mudflats of Berry's Creek and tributaries.

Marsh birds include red-winged blackbird, marsh wren, and swamp sparrow (*Melospiza georgiana*), which were the most abundant species identified during a survey of Oritani Marsh (Barrett and McBrien 2007). An additional 16 species were observed during other times on the site for a total of 39 species observed during 2001 (Barrett and McBrien 2007). Red-winged blackbirds are among the most common and abundant passerine species in the New Jersey Meadowlands (Mizrahi et al. 2007).

Mammal surveys have occurred several times in the past 20 years within the Meadowlands, though not specifically as part of the RI. During a 5-day trapping and observation period in Oritani Marsh in late April 2000, six species of small mammals were documented (Louis Berger Group 2001; Barrett and McBrien 2007). Of these, the meadow jumping mouse (*Zapus hudsonius*) was collected in a trap, and five other species were either directly observed or identified by scat and tracks. These species included muskrat (*Ondatra zibethicus*), eastern cottontail (*Sylvilagus floridanus*), little brown bat (*Myotis lucifugus*), red fox (*Vulpes vulpes*), and raccoon (*Procyon lotor*). Most of the species were collected near the marsh fringes and near roadways outside of the tidal areas that are the focus of the RI. Only meadow jumping mouse and muskrat were found within the interior of the *Phragmites* marsh. Observations by field crews confirmed the muskrat was the mammal most often observed using the waterways and marshes of the BCSA. Deer have been observed swimming in the waterway, and a red fox was observed foraging at the water's edge of BCC during the Phase 3b 2015 field effort.

4.8.2.4 Threatened and Endangered Species

A number of threatened and endangered avian species have been observed in the BCSA. The state endangered northern harrier (*Circus cyaneus*) has been observed nesting within Berry's Creek

Marsh (Kiviat and MacDonald 2002b). State threatened bird species observed in the BCSA per the NJDEP Landscape Project include the bobolink (*Dolichonyx oryzivorus*), yellow-crowned night heron, savannah sparrow (*Passerculus sandwichensis*), and grasshopper sparrow (*Ammodramus savannarum*). RI field teams have observed state threatened bird species in the BCSA study area including osprey (*Pandion haliaetus*) and yellow-crowned night heron. The NJSEA (formerly the New Jersey Meadowlands Commission) has noted breeding nests of the state threatened black-crowned night heron in the Meadowlands area (NJMC 2012), but a more recent report did not find any nesting sites for this species (NJSEA 2015). The BCSA potentially supports a breeding population of the state endangered American bittern (*Botaurus lentiginosus;* Kiviat and MacDonald 2002b), although this species has not been observed by RI field teams. Peregrine falcon (*Falco peregrinus*) may also breed on bridge structures that exist in the BCSA, although this species has not been documented in the study area (NJDEP 2008b).

4.8.3 Marsh Waterway Interactions and the BCSA Food Web

Based on the collective regional and site-specific information, generalized food webs were developed to depict the key receptors and hypothesized connections between them in both waterway and marsh habitats (Figure 2-1).[101] These food webs and receptors are considered in the BERA to assess ecological risks, but also used here to understand trophic linkages that can lead to COPC uptake and transport within the BCSA food webs.

Important to this understanding is the link between marsh and waterway habitats. Although the marshes and waterways support distinct communities, both physical (e.g., organic matter transport) and biological (e.g., feeding/foraging) processes connect the waterway and marsh habitats within the BCSA.

Studies of tidal marshes indicate that production from the wetlands is important to the aquatic food web. *Phragmites* production has been identified as a contributor to the aquatic food web estuarine systems (Wainright et al. 2000) and the marshes of the Meadowlands region have been identified as an important food source for the detritus-based food web of the New York/New Jersey Harbor estuary ecosystem (USFWS 2007). Stable isotope studies (using isotopes of carbon, nitrogen, and sulfur) conducted in the BCSA indicate that it too is a detritus-based food web, with primary production and carbon input by *Phragmites* an important contributor to the fishery aquatic food web.[102]

Organic matter exported from the marshes is the primary source of organic matter within the BCSA waterways (Figure 2-1).[103] Moreover, suspended particulate matter in the water column is

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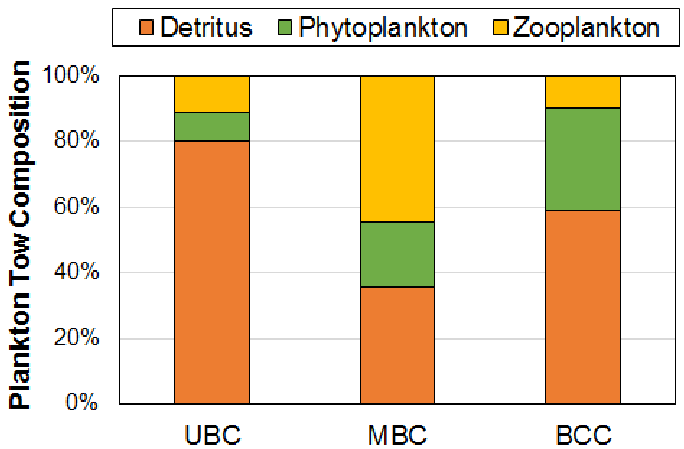
[101] Refer also to Figures 1-2 and 1-3 in Appendix I.
[102] Refer to Attachment I5 of Appendix I.
[103] Refer to Appendices E, F, and H.

dominated by organic detritus (Graphic 11). Plankton tows conducted within the BCSA main channel indicated that detritus was generally the largest contributor to the particle composition at all locations and over all seasons (based on particle counts).[104] Detrital matter typically accounted for a large percentage of the particles collected within the plankton tow. The detritus fraction was observed to consist of plant material in addition to sand, silt, fungal hyphae, and bacteria. Zooplankton and phytoplankton accounted for the remainder of particles collected. Centric diatom size ranges were between 15 and 100 µm in diameter and diatoms were often one of the dominant members of the algae community. Though not quantified, visual examination of the samples indicated that on a mass basis, detritus was by far the dominant source of particles in the water column.



Graphic 11. Average Distribution of Detritus, Phytoplankton, and Zooplankton Observed in Particulate Counts of Plankton Tows

The dominance of detritus in the water column is a reflection of the extensive and highly productive *Phragmites* stands that are open to the tides.

In addition to export of detritus to the waterway, the marshes also provide a foraging habitat for waterway species when the marshes are flooded at high tides. During the RI, mummichog collected after exiting the marshes during ebb tide typically had fuller stomachs[105] than mummichog collected on flood tide. Invertebrates on the marsh surface can be incorporated into the diet of mummichog, and insects and other invertebrates found in marsh detritus were also identified in mummichog guts.[106] Detritus in the leaf litter on the marsh surface also may be incidentally ingested while foraging for food (Allen et al. 1994; Deegan and Garritt 1997; McMahon et al. 2005). Weis and colleagues (2001) found that detritus comprised roughly 65 percent of adult

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[104] Refer to Attachment E4 of Appendix E.
[105] Based on the number of empty guts as well as the mass of material collected to support gut content studies.
[106] Refer to Attachment I5 of Appendix I.

mummichog gut content in Berry's Creek, with the remaining 35 percent consisting of crustaceans, insects, worms, and small fish. This is consistent with the findings in the RI; marsh detritus constituted roughly 50 percent of the gut content of mummichog and white perch, with animal matter making up the remainder of the gut content in both species.[107] Perch are less likely to forage on the marsh surface given their size and foraging habits, but the presence of detritus in the guts of both species indicates the association of marsh-generated detritus to overall dietary exposures.

The linkages between marsh and waterways and the overall structure of the BCSA food web will influence COPC uptake and magnification. Overall, low COPC residues in marsh detritus and the topmost layer of waterway surface sediment (compared to deeper sediments) limit the COPC residues available for uptake. Further, stable isotope data collected as part of the RI also indicated that the BCSA aquatic food web is compressed, with few (~1) trophic steps between primary producers and fish consumers.[108] The flat trophic structure can limit biomagnification of COPCs (see Section 6.3.1 for discussion).

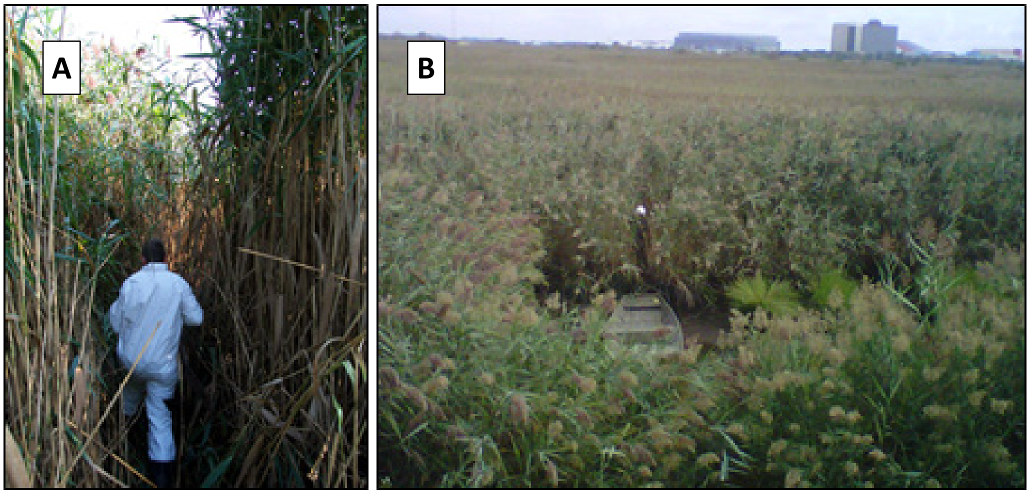
The aquatic food web structure on the BCSA site is not static and shows slight variations among reaches.[109] Shifts in stable isotope ratios can occur due to a wide range of environmental factors in an urban estuarine setting including, but not limited to, season, salinity, and changes in sewage or stormwater input. In the BCSA, the spatial shift in patterns of carbon isotopes from upstream to downstream reaches is consistent with moving from a virtually freshwater environment in the uppermost portion of the BCSA to a system that is more influenced by the more marine waters from the Hackensack River estuary (Peterson and Fry 1987). The observed shift in isotopic ratios in the lower portion of the study area along this salinity gradient is consistent with results from the hydrodynamic modeling and other lines of evidence, which show that the lower portion of the BCSA system is dominated by Hackensack-derived water while the upper reaches have increased influence from freshwater sources (Section 4.7.2).[110]

4.9 Human Use Surveys

The dense stands of *Phragmites* that surround the BCSA waterways limit human access across much of the study area (Graphic 12). Observations by the RI team during the intensive field activities conducted since 2007 indicate that most human activity in the tidal portions of the study area is focused at access points where roadways and bridges meet the creek. Overall, there is a relatively small portion of shoreline (estimated to be less than 3 percent) along the main channel and major tributaries that is both readily accessible to people and composed of relatively hard surfaces (e.g., bridge abutments, parking lots, gravel surface) that could support fishing or crabbing

[107] Refer to Attachment I5 of Appendix I.
[108] Refer to Attachment I5 of Appendix I.
[109] Refer to Attachment I5 of Appendix I.
[110] Refer to Section 2 of Appendix G.

activity from the shore. In addition to this very limited land access, access to the BCSA can occur via boat from the Hackensack River.



Graphic 12. Typical Stand of *Phragmites* Surrounding the BCSA Waterways (A) and Dense Stands of *Phragmites* Surrounding a Sampling Team Boat within the BCSA Waterway (B)

Human activity within the tidal portions of the BCSA was recorded throughout the course of the RI to assist in understanding human exposure pathways and frequency. Camera surveys and field observations of activity occurred throughout the RI study.[111]

In Phase 1, cameras were placed throughout BCSA reaches at four locations known to be used by people to access the tidal portions of the BCSA waterway. The cameras were deployed for a period of 4 months (summer–fall 2009) taking photos in daylight every 30 minutes. The Phase 2 program was run for an entire year (July 20, 2010–July 26, 2011) with improved camera technology. Cameras were installed at five locations and programmed to take photos every 30 minutes. Following the Phase 2 program, consumption advisory signs were posted at many of the known waterway access points. The subsequent Phase 3 monitoring program conducted from June 10, 2014 to December 15, 2014, used the same camera technology as Phase 2, but was focused on those access points where the consumption advisory signs were posted. Collectively across all phases, photographs were taken on more than 700 days. Photographs taken during all sampling phases were viewed to identify those in which people or signs of human use (e.g., fishing pole) were present. For these photographs, the type, location, day of the week, and month of activity was reported and recorded in a database.

[111] Refer to Appendix N.

Observations of human activity by the RI field team were recorded using field forms and compiled in a database. Approximately 70,000 hours of observation time occurred during the RI study, based on the number of man hours for deployed field staff.

The camera survey documented human use of the BCSA. Activity varied by location. Boating in BCC and fishing at the Route 3 Bridge were the most common activities but were observed infrequently. Across 724 cumulative observation days in BCC, boating was observed on 68 days (9 percent). Fishing at the Route 3 Bridge occurred even less frequently, being observed on 32 out of 531 observation days (6 percent) at that location. Crabbing was observed occasionally, primarily at the Paterson Plank Road overpass, but only on 7 of 704 observation days (1 percent) at that location.

Direct observations by the RI field crew corroborated the findings of infrequent human activity based on the camera survey. Across the 7-year RI study period, a total of 71 human use events were recorded, most often occurring at the known access points monitored by the cameras. Of the 71 recorded events, fishing was the most frequent activity, observed on 38 instances and occurring primarily at the bank of the southern-most tributary of Paterson Plank Marsh, Paterson Plank Road Overpass, and Route 3 Bridge areas (Figure 1-2).

The camera study and recorded field observations provide a robust data set with which to characterize typical human use activities (exposure pathways and exposure frequency) in the BCSA. Overall, human use of the BCSA is infrequent and localized, occurring primarily at the known limited waterway access points. The findings of the study are considered in the baseline human health risk assessment to provide a site-specific context to the exposure pathway and frequency assumptions that are used to calculate risks.[112]

[112] Refer to Appendices L and M.

SECTION 5

CHEMICAL SYSTEM CHARACTERIZATION

The form, distribution, and bioavailability of COPCs in BCSA abiotic and biotic media are influenced by a variety of chemical, physical, and biological factors. The following discussion focuses on total mercury, methyl mercury, and PCBs (total Aroclors).[113] As noted previously, these three chemicals have been identified as the primary COPCs, and other COPCs generally follow a similar distribution. Appendices E, F, and I present detailed descriptions of the nature and extent of the primary COPCs in surface water, sediment, and tissue samples collected from the BCSA and the reference sites. However, all chemicals that exceed screening criteria are considered in the risk assessments.[114]

5.1 Distribution of COPCs in BCSA Sediment

The distribution of the primary COPCs in BCSA sediment reflects the distribution of historical sources to the BCSA tidal zone and surrounding watershed, the physical characteristics that dictate water flow and sediment transport within the BCSA, and the chemical characteristics of the COPCs—most notably their strong association with the particulate phase and POC. A majority of the historical industrial sources were located in or had discharges that entered the UBC and MBC (Section 6.1). Higher COPC concentrations (particularly mercury and PCBs) are evident in sediment in the upper reaches (UBC, MBC) of the BCSA due to this proximity to historical sources (Graphic 13). COPC concentrations in the lower system (BCC, LBC) are more similar to the reference areas. This pattern is evident for both waterway and marsh sediments.

The following presents a summary of the distribution of mercury and PCBs in surface and subsurface sediment in the BCSA. Methyl mercury is generated *in situ* as a product of microbially-mediated processes. As a result, its distribution differs from that of mercury and PCBs and is discussed separately. For the purposes of the RI, surface sediment has been defined as the BAZ for waterway sediment (0–6 cm for UBC, 0–10 cm for all other areas; Section 3.2) and as 0–5 cm for marsh sediment.[115] Statistical comparisons of COPC concentrations in BCSA sediments are made to the concentrations in reference site sediments using a Mann-Whitney U-test.[116]

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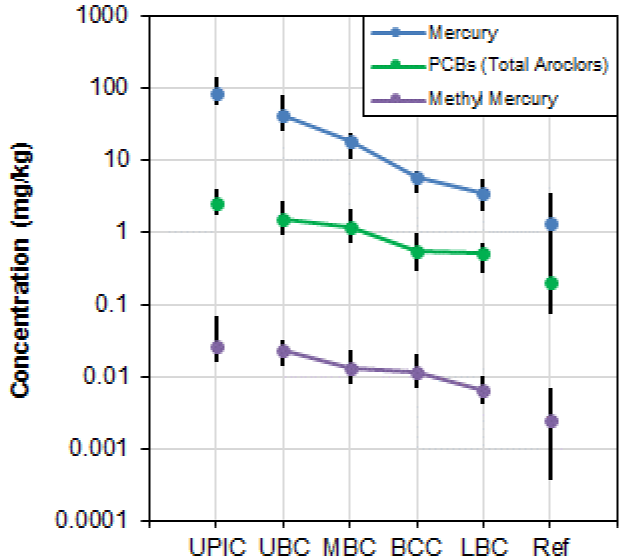
[113] PCBs are reported as the sum of detected Aroclors (see Appendix K for data summation procedures).
[114] Refer to Appendices L and M.
[115] As discussed in Appendix I and in Section 4.8.2.1, the majority of marsh macroinvertebrate activity occurs in the detrital mat on the surface of the marsh. Few organisms occur within the marsh sediment column below that and those that do predominate in the top 0-2 cm of marsh sediment (Graphic 10). Therefore, the 0–5 cm increment used to define marsh surface sediment should not be considered the BAZ in the marsh.
[116] Refer to Section 3.3.2 of Appendix F.



Graphic 13. COPC Concentrations in Waterway Surface Sediment (Median, 25th, and 75th Percentiles)

5.1.1 Mercury and PCBs in Waterway and Marsh Sediments

The following presents an overview of the distribution of mercury and PCBs in waterway and marsh surface sediment. A detailed analysis of the distributions of these COPCs is presented in Section 3.3.2 of Appendix F, including associated graphical and tabular data presentations.

5.1.1.1 Mercury and PCBs in Waterway and Marsh Surface Sediments

Total mercury and PCB concentrations in surface sediment decrease from north to south across the BCSA (Graphic 13). Based on median concentrations, the highest concentrations of mercury and PCBs are observed in waterway and marsh sediments from UPIC and UBC, intermediate concentrations in MBC, and concentrations approaching regional background levels in BCC and LBC. Figures 5-1 and 5-2 present a map view of the total mercury and PCB concentrations measured in BCSA surface sediment. Tables 5-1 and 5-2 present summary statistics (median, 25th and 75 percentile) for total mercury and PCB concentrations in waterway and marsh surface sediment. The following summarizes key findings related to the distribution of total mercury and PCBs in waterway surface sediment.

Total Mercury (Figure 5-1, Tables 5-1 and 5-2)

- Within the tidal zone (UBC, MBC, BCC, LBC), median mercury concentrations in marsh surface sediments are on average 1.7 times lower than mercury concentrations in waterway surface sediment across all 4 reaches (Tables 5-1 and 5-2). The lower mercury concentrations in marsh surface sediments compared to waterway surface sediments are likely attributable in part to the incorporation of relatively clean (Section 5.3) organic matter derived from marsh vegetation (marsh sediment typically ~20 percent organic matter).[117]

- The highest total mercury concentrations are in UPIC sediment. Further, unlike in the tidal zone, total mercury concentrations are higher (~4 times) in marsh sediment than in tributary sediment in UPIC.

- The highest total mercury concentrations in tidal zone surface sediment occur in UBC. The greatest concentrations (>175 mg/kg) most commonly occur in the waterways of the northernmost portion of UBC (Figure 5-1). Total mercury concentrations in MBC waterway and marsh surface sediment are ~2.6 times lower than the concentrations in UBC waterway and marsh surface sediment; and total mercury concentrations in BCC and LBC waterway and marsh surface sediment are 2.3 to 5.1 times lower, respectively, than in MBC waterway and marsh surface sediment (based on median concentrations, Tables 5-1 and 5-2).

- As is shown in Figure 5-1, total mercury concentrations in the majority (90 percent) of the waterway samples in BCC and LBC are <10 mg/kg, and about one-quarter of the waterway samples collected from these two reaches are less than 2.5 mg/kg total mercury. Similarly, total mercury concentrations in all of the marsh samples in BCC and LBC are <10 mg/kg, and about one-half of the waterway marsh samples collected from these two reaches are less than 2.5 mg/kg total mercury.

- Total mercury concentrations in LBC marsh surface sediment are not statistically different from the concentrations in surface sediment in reference site marshes.[118]

- Total mercury concentrations in BCC and LBC waterway surface sediment and BCC marsh sediment are statistically greater than in the reference sites; however, there is considerable overlap in the range of concentrations in BCC/LBC with the reference site concentrations (e.g., the 25th percentile concentrations of the BCC and LBC sediments is less than the 75th percentile of the reference site sediments; Tables 5-1 and 5-2).

- With the exception of UPIC, the concentration of total mercury in surface sediment from the Above Tide Gate Areas (East Riser, West Riser, and Rutherford ditches) are generally low (medians = 0.1 to 5.5 mg/kg) and are comparable to mercury concentrations in reference site waterway sediment (median = 1.3 mg/kg).[119]

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[117] Refer to Section 3.2.2 of Appendix F.
[118] Refer to Figure 3-10 of Appendix F.
[119] Refer to Section 3.3.2 of Appendix F.

Table 5-1. Total Mercury Concentrations (mg/kg) in Waterway Surface Sediment

Area	Percent Detected	Median	25th Percentile	75th Percentile
Above Tide Gate				
UPIC	100	87	58	140
BCSA Tidal Zone				
UBC	100	43	24	79
MBC	98	18	10	24
BCC	100	5.9	3.4	7.0
LBC	99	3.5	2.0	5.3
Reference Sites				
Ref Sites	89	1.3	0.26	3.4

Table 5-2. Total Mercury Concentrations (mg/kg) in Marsh Surface Sediment

Area	Percent Detected	Median	25th Percentile	75th Percentile
Above Tide Gate				
UPIC	100	350	130	616
BCSA Tidal Zone				
UBC	99	20	16	31
MBC	100	8.2	5.9	11
BCC	100	3.5	2.8	4.8
LBC	100	2.1	1.1	2.7
Reference Sites				
Ref Sites	100	2.3	1.0	2.8

PCBs (Figure 5-2, Tables 5-3 and 5-4)

- As for mercury, PCB concentrations in tidal zone sediments are appreciably lower in the marshes than in the waterways. Based on median concentrations, PCB concentrations in the marshes are lower than in the waterways by approximately 4 times in UBC and MBC, and by 5 to 7.5 times in LBC and BCC (Tables 5-3 and 5-4).

- More than 80 percent of PCB concentrations in the BCSA tidal zone surface sediment samples are ≤2 mg/kg (Figure 5-2).[120] The highest PCB concentrations in tidal zone surface sediment occur in the UBC waterway (Figure 5-2). Concentrations exceed 15 mg/kg in tributaries and mudflats in the northernmost portion of UBC and in the mudflat immediately adjacent to the

[120] Refer to Figure 3-20 of Appendix F.

East Riser tide gate. Median PCB concentrations in MBC waterway and marsh surface sediments are 1.3 to 1.6 times less than in UBC waterway and marsh surface sediments (Tables 5-3 and 5-4); however, the difference in concentration was only found to be statistically significant for the marsh sediments.[121] The highest concentrations in MBC most typically occur in the upper half of MBC, with several localized areas with concentrations >5 mg/kg (Figure 5-2). Median PCB concentrations in BCC and LBC waterway and marsh surface sediments are 2.2 to 3.9 times less than in MBC waterway and marsh surface sediments.

- PCB concentrations in BCC and LBC marsh surface sediments are not statistically different from the reference sites.[122]

- PCB concentrations in BCC and LBC waterway surface sediment are statistically greater than in the reference sites; however, there is considerable overlap in the range of concentrations in BCC/LBC with the reference site concentrations (e.g., the 25th percentile concentrations of the BCC and LBC sediments is less than the 75th percentile of the reference site sediments; Tables 5-3 and 5-4).

- With the exception of UPIC, the concentrations of PCBs in surface sediment from the Above Tide Gate Areas (East Riser, West Riser, and Rutherford ditches) are generally low (medians = 0.23 to 0.26 mg/kg) and are comparable to reference site concentrations (median = 0.20 mg/kg).[123]

Table 5-3. PCB Concentrations (mg/kg) in Waterway Surface Sediment

Area	Percent Detected	Median	25th Percentile	75th Percentile
Above Tide Gate				
UPIC	100	2.5	1.7	3.9
BCSA Tidal Zone				
UBC	99	1.5	0.88	2.7
MBC	98	1.2	0.68	2.1
BCC	98	0.54	0.28	0.93
LBC	97	0.49	0.26	0.69
Reference Sites				
Ref Sites	94	0.20	0.075	0.44

[121] Refer to Figure 3-12 of Appendix F.
[122] Refer to Table 3-6 of Appendix F.
[123] Refer to Section 3.3.2 of Appendix F.

Table 5-4. PCB Concentrations (mg/kg) in Marsh Surface Sediment

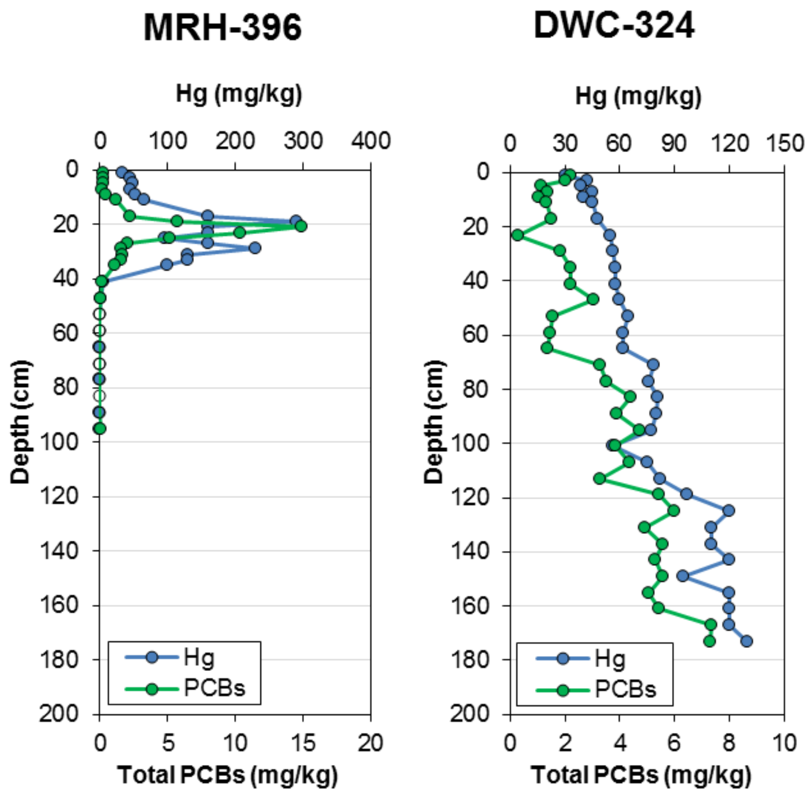
Area	Percent Detected	Median	25th Percentile	75th Percentile
Above Tide Gate				
UPIC	100	1.1	0.28	2.7
BCSA Tidal Zone				
UBC	97	0.41	0.23	0.86
MBC	100	0.26	0.14	0.52
BCC	85	0.10	0.063	0.22
LBC	94	0.066	0.044	0.13
Reference Sites				
Ref Sites	86	0.067	0.039	0.12

5.1.1.2 Vertical Distribution of Mercury and PCBs in Waterway and Marsh Sediments

Deposition of particulate-bound mercury and PCBs occurred when historical discharges were at a maximum (1950s–1960s), and subsequent burial by progressively cleaner sediments over time has resulted in the highest concentrations typically present at depth in the vertical sediment profile. As with surface sediment, a gradient of decreasing concentration from north to south is also observed for mercury and PCBs at depth.[124] This pattern of natural recovery is evident in the COPC profiles measured in high-resolution cores (see examples shown in Graphic 14) and in the comprehensive inventory of all of the sediment mercury and PCB concentration data provided in Attachments F1 and F6 of Appendix F.

In the marsh sediments, the maximum mercury and PCB concentrations associated with historical maximum sources occur as relatively clear peaks, with both COPC peaks typically occurring at similar depths within a given marsh. The peak concentrations occur at a generally consistent depth within a given marsh, but vary somewhat between marshes.[125] Mercury and PCB subsurface maxima typically occur at depths of approximately 20 cm in UBC and MBC marsh sediment. In the BCC marshes, the subsurface maximum depths are somewhat deeper than in the upper reaches (approximately 40 cm). Lower sediment deposition rates were measured in LBC marsh cores, and these cores show comparatively shallower average subsurface maximum depths (approximately 10 cm). The consistent observation of distinct peaks concentrations at depth and monotonic decrease in concentration towards the surface is consistent with the net depositional function of the marshes. Concentrations in the top-most sample interval (0–2 cm) of high-resolution marsh cores are typically at least an order of magnitude less than the peak concentrations at depth.

[124] Refer to Section 3.3.3 of Appendix F.
[125] Refer to Attachment F1 of Appendix F.



Graphic 14. Example Vertical Profiles of COPC Concentrations in Waterway (right) and Marsh (left) High-Resolution Cores

Peak concentrations of mercury and PCBs occur in subsurface sediment throughout the majority of the BCSA waterways, with 100 (mercury) and 92 (PCBs) percent of the high-resolution cores exhibiting a pattern of declining concentrations from the subsurface toward the sediment surface.[126] The depth to the subsurface maxima for mercury and PCBs is more variable in the waterways than in the marshes (median depth ranging from 31 [UPIC] to 86 [BCC] cm below the surface)[127], depending on morphology and location in the system (e.g., proximity to an entry point of upland storm flows). Vertical profiles of mercury and PCB concentrations in waterway sediment reflect varying sediment processes and episodic resuspension of surface sediment in relation to localized velocity profiles during relatively rare, large storm events.

UPIC is an exception to the patterns noted above for the tidal portions of the BCSA, as the majority of marsh cores have the highest total mercury and PCB concentrations closer to (within the top 10 cm) the surface. The placement of a tide gate in 1967–1968 on PIC near Gotham Parkway (Figure 1-2) largely isolated this marsh area from tidal flows and associated sediment input. This

[126] Refer to Table 2b of Attachment F1, Appendix F.
[127] Refer to Table 3-7 of Appendix F.

portion of the BCSA has a very small drainage area, and therefore has a limited sediment supply to facilitate burial of higher concentration material over time at the same rate that is observed elsewhere in the study area. This had the effect of reducing the amount of sediment deposition and slowing the rate of burial of historical contamination.

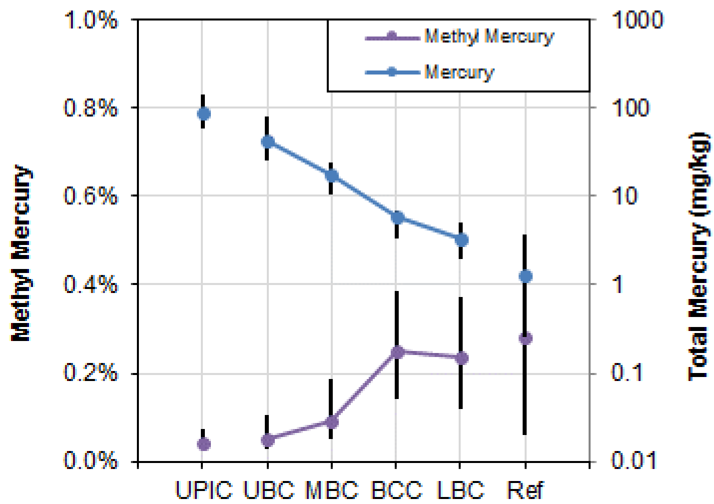
5.1.2 Methyl Mercury in Waterway and Marsh Sediments

Methyl mercury is produced *in situ* as a by-product of microbially-mediated processes (Section 6.2.2). In contrast to the other two primary COPCs, methyl mercury distribution is more a function of geochemical factors than depositional history. In the waterway, maximum methyl mercury concentrations are typically at or very close to the sediment surface (typically within the top 2 cm). In the marsh, peak methyl mercury concentrations typically occur as a more diffuse peak, generally at depths ranging from 10–20 cm below the surface. While the depth to peak methyl mercury concentrations is somewhat variable across locations, this pattern (shallow in the waterway, deeper in the marsh) is generally consistent throughout the BCSA.

5.1.2.1 Methyl Mercury in Waterway and Marsh Surface Sediments

Figure 5-3 presents a map view of the methyl mercury concentrations measured in BCSA surface sediment. Tables 5-5 and 5-6 present summary statistics (median, 25th and 75 percentile) for methyl mercury concentrations in waterway and marsh surface sediments. The following summarizes key findings related to the distribution of methyl mercury in waterway and marsh surface sediment:

- Although methyl mercury concentrations in surface sediment generally follow the pattern of declining concentrations from the upper to lower tidal zone reaches similar to total mercury, the decrease in concentration is considerably less pronounced (Graphic 13). As a result, an inverse relationship is observed between the percent methyl mercury and total mercury concentration (i.e., the fraction of total mercury that is methylated decreases as total mercury concentrations increase) across the BCSA (Graphic 15). Similar trends have been noted at other sites with relatively high total mercury concentrations, suggesting that methyl mercury concentrations are a function of not only mercury concentrations, but also geochemical variables (e.g., sulfide speciation, partitioning to organic matter) and microbial controls (e.g., productivity, demethylation) that play an important role in limiting methyl mercury concentrations (Krabbenhoft et al. 1999; Benoit et al. 2003). The role of sulfide mineral formation, binding to organic matter, and other factors on the availability of mercury for methylation are discussed further in Section 6.2.2 and Appendix H.



Graphic 15. Percentage of Methyl Mercury and Total Mercury Concentration in Waterway Surface Sediment (Median, 25th, and 75th Percentiles)

- In contrast to total mercury and PCBs, marsh surface sediment methyl mercury concentrations are higher than waterway surface sediment concentrations by a factor of 1.4 to 2.5 based on median concentrations (Tables 5-5 and 5-6). These results reflect the differing physical and geochemical environments of these two settings (Sections 6.2.1 and 6.2.2) and the associated vertical distribution of methyl mercury in near-surface marsh and waterway sediments (Section 5.1.3).

- The highest methyl mercury concentrations in surface sediment occur in UBC and UPIC waterways and marshes. Unlike mercury, methyl mercury is not substantially elevated in UPIC surface sediment compared to UBC surface sediment (Table 5-5). Further, the locations with the highest methyl mercury concentrations throughout the site are often not co-located with the locations where the highest total mercury concentrations were observed (Figure 5-3). These data support the hypothesis that site-specific geochemical and microbiological processes play an important role in net mercury methylation.

- Methyl mercury concentrations in BCC and LBC marsh surface sediment are not statistically different from the reference sites.[128]

- Methyl mercury concentrations in BCC and LBC waterway surface sediment and LBC marsh sediment are statistically greater than in the reference sites[129]; however, there is considerable overlap in the range of concentrations in BCC/LBC with the reference site concentrations

[128] Refer to Figure 3-11 of Appendix F.
[129] Refer to Table 3-4 of Appendix F.

(e.g., the 25th percentile concentrations of the BCC and LBC sediments is equal to or less than the 75th percentile of the reference site sediments; Tables 5-5 and 5-6).

- With the exception of UPIC, the concentration of methyl mercury in surface sediment from the Above Tide Gate Areas (East Riser, West Riser, and Rutherford ditches) are generally low (medians = 0.004 to 0.008 mg/kg) and are comparable to mercury concentrations in reference site waterway sediment (median = 0.007 mg/kg).[130]

Table 5-5. Methyl Mercury Concentrations (mg/kg) in Waterway Surface Sediment

Area	Percent Detected	Median	25th Percentile	75th Percentile
Above Tide Gate				
UPIC	100	0.026	0.016	0.067
BCSA Tidal Zone				
UBC	100	0.023	0.014	0.032
MBC	100	0.013	0.008	0.024
BCC	96	0.012	0.007	0.020
LBC	97	0.006	0.004	0.010
Reference Sites				
Ref Sites	91	0.003	0.0004	0.007

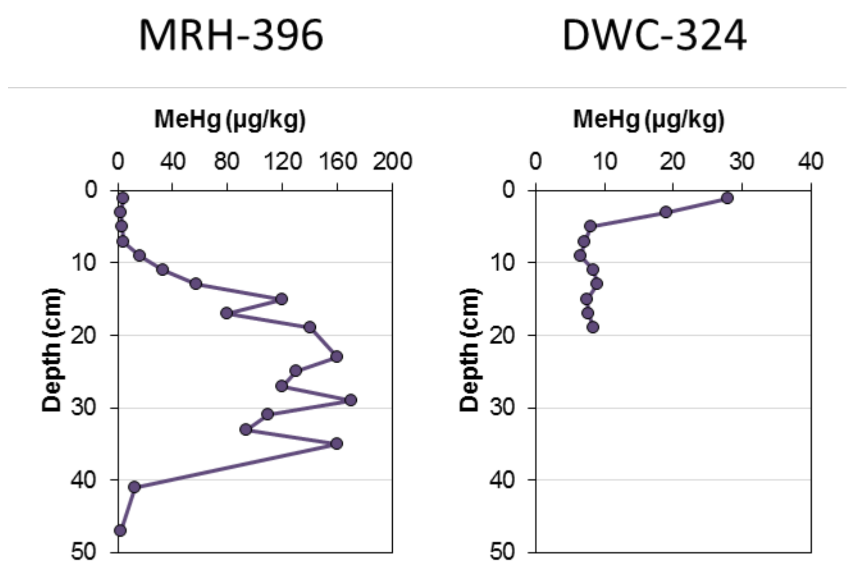
Table 5-6. Methyl Mercury Concentrations (mg/kg) in Marsh Surface Sediment

Area	Percent Detected	Median	25th Percentile	75th Percentile
Above Tide Gate				
UPIC	100	0.034	0.021	0.074
BCSA Tidal Zone				
UBC	100	0.032	0.018	0.052
MBC	100	0.022	0.010	0.034
BCC	100	0.016	0.008	0.024
LBC	100	0.016	0.009	0.023
Reference Sites				
Ref Sites	94	0.008	0.002	0.019

[130] Refer to Section 3.3.2 of Appendix F.

5.1.2.2 Vertical Distribution of Methyl Mercury in Waterway and Marsh Surface Sediments

Maximum methyl mercury concentrations occur within the top 0–2 cm of sediment in 50 percent of waterway high-resolution cores and within the top 0–4 cm of sediment in 73 percent of the cores. Methyl mercury concentrations typically decrease sharply in deeper waterway sediment, typically reaching a concentrations of less than 15 µg/kg in the 4–6 cm sample interval (Graphic 16).



Graphic 16. Example Vertical Profiles of Methyl Mercury Concentrations in Waterway (right) and Marsh (left) High-Resolution Cores

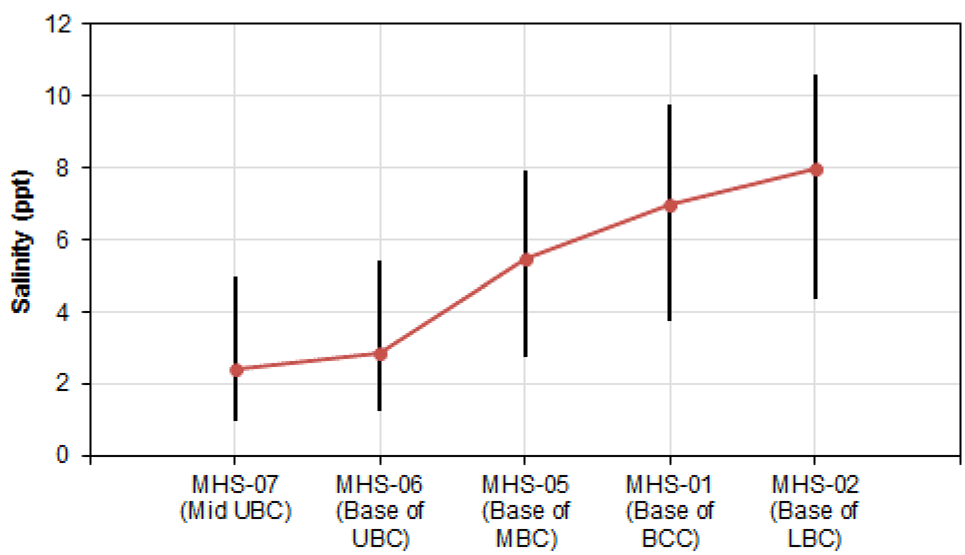
By contrast, the maximum methyl mercury concentration occurs in the subsurface (i.e., below 0–2 cm) for the majority (93 percent) of the high-resolution core locations from the BCSA marshes. The depth of the maximum methyl mercury concentration varies in the marsh cores, typically occurring as a diffuse peak at depths of 10 to 20 cm below the sediment surface (Graphic 16). The contrast in the vertical distribution of methyl mercury between waterway and marsh sediment primarily relates to the shallower onset of anoxic conditions in waterway sediment where methyl mercury production is favored (Section 6.2.2).

Methyl mercury concentrations in UPIC marsh sediment also occur in the subsurface, but at a shallower depth than in the tidal zone marshes. Peak methyl mercury concentrations occur in the 4–10 cm depth range in UPIC marsh sediment.

5.2 Surface Water COPCs Distribution

Conditions within the tidal zone of the BCSA are influenced by tidal interactions with the Hackensack River estuary and by uplands flows, including baseflow and episodic storm flows. As described in Section 4.7.2, the majority of the time flow in the BCSA is dominated by tidal exchange with the Hackensack River estuary (Graphic 6). Tidal influences are most prominent in the lower reaches, which are close to the Hackensack River and nearly completely exchange with the river during each tidal cycle. Although tidal flows also dominate in the upper reaches, tidal influences decrease with distance from the river as the BCSA main channel shallows and the relative volume of freshwater baseflow and storm flow increases. UBC and MBC are characterized by longer residence times (3 to 6 days) and less frequent exchange with the Hackensack River than LBC and BCC (residence times on the order of 1 day) (Graphic 7).

Based on continuous monitoring throughout the BCSA main channel in 2009 through 2011, salinity decreases from mesohaline conditions in the lower BCSA reaches near the exchange points with the Hackensack River (median of approximately 7 to 8 ppt) to oligohaline conditions in the upper reaches (median of 2.4 ppt in UBC) where the relative freshwater influence is greatest (Graphic 17). Salinity levels in the BCSA and in the Hackensack River estuary have been on the rise in recent years based on data collected over the course of the BCSA RI and collected in the river by the Meadowlands Environmental Research Institute (MERI 2015).[131]

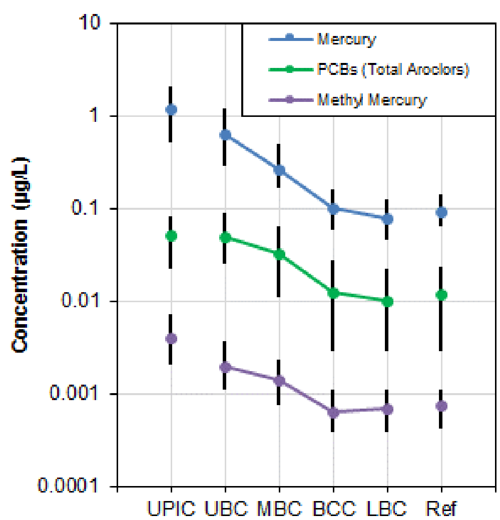


Graphic 17. Salinity in BCSA Surface Water (Median, 25th and 75th Percentiles)[132]

[131] Refer to Section 3.1 of Appendix E.
[132] Analysis represents the high-frequency data collected under the moored station water quality parameter monitoring completed during RI Phases 1 and 2 (2009 to 2011).

Regional influences on surface water quality (such as low dissolved oxygen and elevated ammonia related to sewage discharges to the Hackensack River) are most prominent in LBC and BCC. As described in Section 4.7.4, the dissolved oxygen concentration is lower in LBC and BCC compared to MBC and UBC, and that suggests oxygen-demanding organic material is carried into the BCSA as a result of tidal exchange with the Hackensack River estuary.

Comparison of results in paired unfiltered and filtered samples collected over the course of the RI shows that the primary COPCs are principally associated (on average 96 percent for mercury, 78 percent for methyl mercury, and 86 percent for PCBs) with the particulate phase in BCSA surface water (Tables 5-7 to 5-9). A north-to-south gradient of decreasing COPC concentration is observed in surface water (Graphic 18) that follows the same broad spatial pattern observed in site surface sediment (Graphic 13, Section 5.1). Similar to surface sediment, the highest concentrations of mercury and methyl mercury occur in UPIC. Surface water PCB concentrations in unfiltered samples are nearly equivalent between UPIC and UBC. Median COPC concentrations in unfiltered samples are 1.4 to 2.4 times higher in UBC than MBC, while median concentrations in MBC are 2.1 to 3.5 times the median concentrations in BCC and LBC.



Graphic 18. COPC Concentrations in Unfiltered Surface Water (Median, 25th and 75th Percentiles)[133]

Statistical testing indicates that the methyl mercury concentrations in UPIC, UBC, and MBC are greater than the concentrations measured in samples collected from the three reference sites and

[133] Analysis represents the discrete non-storm and storm data collected during RI Phases 1 and 2 (2009–2011) and the BMP (2011–2015).

that the difference is statistically significant.[134] Concentrations in BCC and LBC, however, were not found to be statistically different from the concentrations measured in the BCSA reference sites (Tables 5-7, 5-8, and 5-9).[135]

Table 5-7. Total Mercury Concentrations (µg/L) in Discrete Filtered and Unfiltered Surface Water in UPIC, BCSA Tidal Zone Reaches, and Reference Sites

Area	Filtered Samples			Unfiltered Samples		
	Median	25th Percentile	75th Percentile	Median	25th Percentile	75th Percentile
Above Tide Gate Area						
UPIC	0.052	0.0078	0.25	1.2	0.51	2.1
BCSA Tidal Zone						
UBC	0.0076	0.0050	0.012	0.64	0.29	1.9
MBC	0.0050	0.0023	0.012	0.27	0.17	0.49
BCC	0.0018	0.0013	0.0025	0.10	0.060	0.16
LBC	0.0018	0.0013	0.0026	0.078	0.047	0.13
Reference Sites						
Reference	0.0017	0.0011	0.0023	0.094	0.063	0.14

Notes: Analysis represents the discrete non-storm and storm data collected during RI Phases 1 and 2 (2009–2011) and the BMP (2011–2015).

With the exception of UPIC, the concentration of total mercury in surface water from the Above Tide Gate Areas (East Riser, West Riser, and Rutherford ditches) are generally similar to the concentrations measured in surface water from BCC, LBC, and the reference locations.[136] These data suggest that upland input to the tidal zone is not the primary source of COPCs to the BCSA tidal zone.

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[134] Tests of statistical significance between each reach and the reference site data were conducted using a Mann-Whitney U-test, with statistical difference at a *p*-value <0.05. Comparisons across the reaches were pairwise Mann−Whitney U tests with *p*−value adjustment for multiple comparisons. Refer to Section 4.1 of Appendix E.

[135] Refer to Tables 4-2, 4-4, and 4-6 of Appendix E.

[136] COPC concentrations in surface water samples collected from the West Riser Ditch prior to the replacement of the tide gate in June 2014 were comparable to the concentrations measured in UBC and MBC. After replacement of the tide gate, COPC concentrations were considerably lower, indicating that surface water samples prior to June 2014 were influenced by tidal flow of water from UBC up the West Riser Ditch during high tide periods. Refer to Section 4.4 and Figure 17 of Appendix D.

Table 5-8. Methyl Mercury Concentrations (µg/L) in Discrete Filtered and Unfiltered Surface Water in UPIC, BCSA Tidal Zone Reaches, and Reference Sites

Area	Filtered Samples			Unfiltered Samples		
	Median	25th Percentile	75th Percentile	Median	25th Percentile	75th Percentile
Above Tide Gate Area						
UPIC	0.0011	0.00031	0.0032	0.0041	0.0021	0.0072
BCSA Tidal Zone						
UBC	0.00030	0.00022	0.00038	0.0020	0.0011	0.0037
MBC	0.00021	0.00011	0.00045	0.0014	0.00075	0.0024
BCC	0.000077	0.000056	0.00013	0.00065	0.00038	0.0011
LBC	0.00011	0.000065	0.00024	0.00068	0.00039	0.0011
Reference Sites						
Reference	0.000086	0.000063	0.00012	0.00076	0.00042	0.0011

Notes: Analysis represents the discrete non-storm and storm data collected during RI Phases 1 and 2 (2009–2011) and the BMP (2011–2015).

Table 5-9. PCBs (Total Aroclors) Concentrations (µg/L) in Discrete Filtered and Unfiltered Surface Water in UPIC, BCSA Tidal Zone Reaches, and Reference Sites

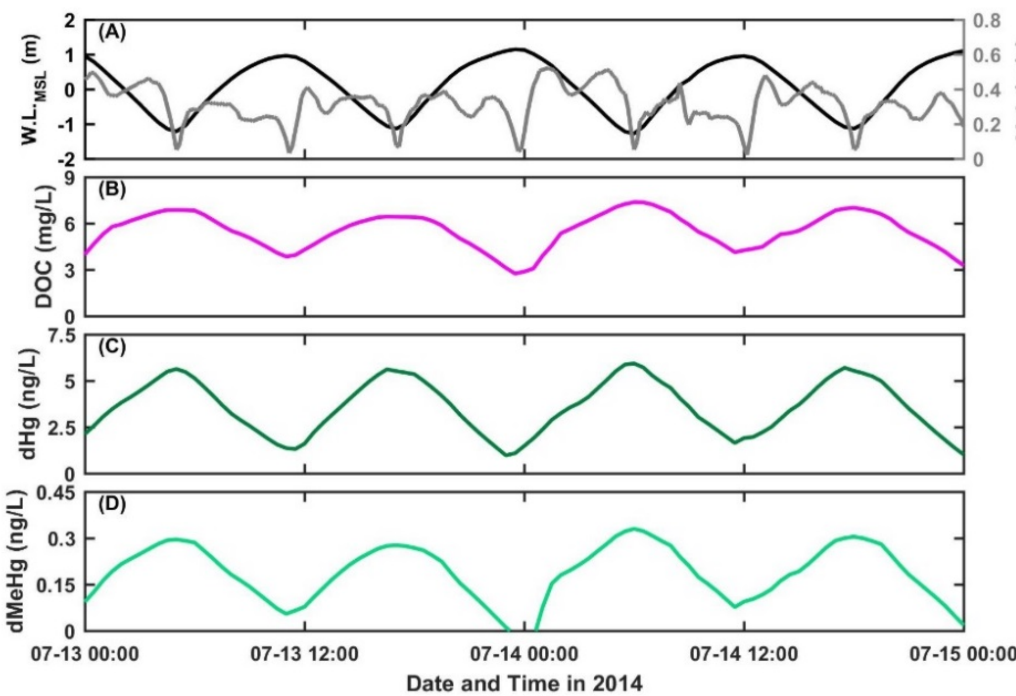
Area	Filtered Samples[137]			Unfiltered Samples		
	Median	25th Percentile	75th Percentile	Median	25th Percentile	75th Percentile
Above Tide Gate Area						
UPIC	0.0029	0.0028	0.0030	0.052	0.022	0.083
BCSA Tidal Zone						
UBC	0.0030	0.0028	0.020	0.049	0.026	0.089
MBC	0.0029	0.0028	0.0095	0.033	0.011	0.065
BCC	0.0029	0.0028	0.0039	0.013	0.0029	0.028
LBC	0.0029	0.0028	0.0032	0.010	0.0029	0.022
Reference Sites						
Reference	0.0030	0.0028	0.0039	0.012	0.0029	0.023

Notes: Analysis represents the discrete non-storm and storm data collected during RI Phases 1 and 2 (2009–2011) and the BMP (2011–2015).

[137] PCBs were nondetect in 76 percent of filtered surface water samples. Because these calculations assume a concentration equal to the detection limit, the median and 25th percentile concentrations in filtered samples are similar or equivalent.

5.2.1 Temporal Patterns

Data collected throughout the course of the RI demonstrate that concentrations in both filtered and unfiltered surface water samples can vary by as much as an order of magnitude over short time scales (hours, days) as a result of tidal water movement and particulate resuspension and deposition processes (Graphics 19 and 20).[138] As noted above, UBC and MBC are characterized by residence times of 3 to 6 days and, although a portion of the water in these reaches moves to downstream reaches as the tide ebbs from high to low tide, it does not reach the Hackensack River on a single ebb tide. This water is then pushed back up the system as lower concentration water moves into the system with the subsequent flood tide. This back-and-forth movement of water within the system results in an oscillating pattern in COPC concentration at any one location in the system, as higher concentration water moves downstream during ebb tide and lower concentration water moves upstream during flood tide (Graphic 19).

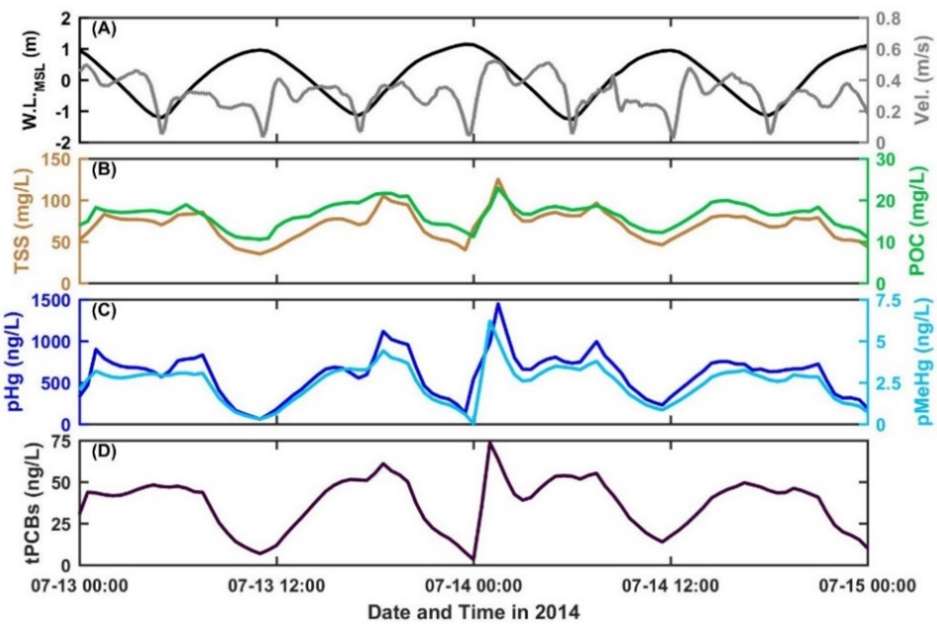


Note: W.L. = water level, Vel. = velocity, DOC = dissolved organic carbon, dHg = dissolved mercury, and dMeHg = dissolved methyl mercury.

Graphic 19. Example of Tidal Patterns in Dissolved-Phase Concentrations Based on Optical Model Results for Station MHS-05 Located at the Base of MBC

[138] Refer to Section 4.3 of Appendix E.

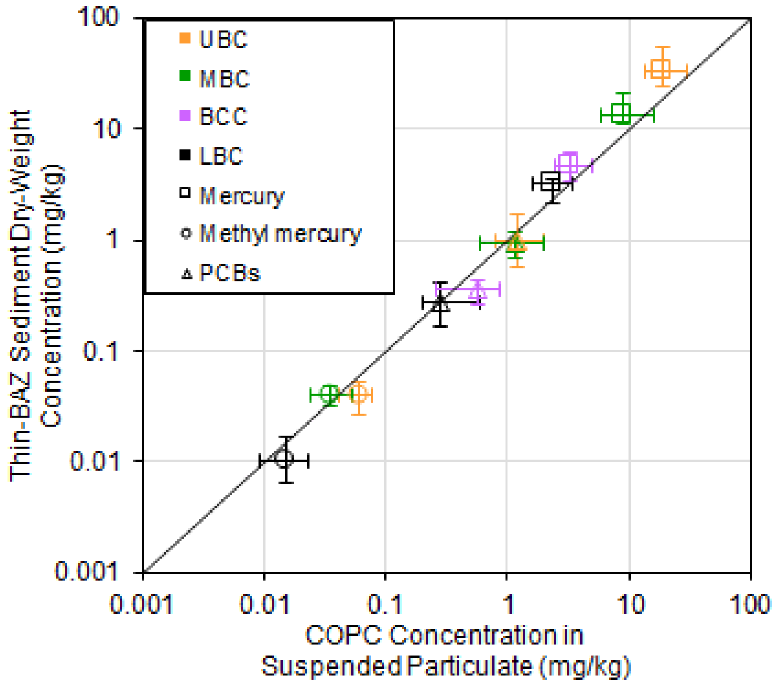
The primary COPCs are principally associated with the particulate phase in BCSA surface water and are strongly influenced by routine and episodic particulate resuspension and deposition processes.[139] As is discussed in Section 4.7.3, suspended particulates deposit to and resuspend from the fluff layer at the surface of the waterway sediment bed in response to fluctuations in channel velocities and other processes such as wind-driven wave action and direct rainfall on exposed mudflats.[140] Particulate-bound COPCs are transported to the surface water column as particulates are resuspended from the fluff layer. This process, coupled with the tidal oscillation process described above, results in a variable pattern in concentration across the flood/ebb tidal cycle, with peak concentrations often coinciding with periods of peak channel velocity (typically in the early stages of the flood and ebb stage; Graphic 20). Further, surface water particulate COPC concentrations are closely related to COPC concentrations at the surface of the waterway sediment bed. On a tidal reach basis, there is nearly a 1:1 correlation between COPC concentrations at the surface (0–2 cm) of the waterway sediment bed and the COPC concentrations in particulates suspended in the surface water column when evaluated on a reach-wide basis (Graphic 21).



Note: W.L. = water level, Vel. = velocity, pHg = particulate mercury, pMeHg = particulate methyl mercury, and tPCBs = total PCBs.

Graphic 20. Example of the Influence of Fluff Layer Resuspension during Peak Tidal Velocity on Particulate Concentrations Based on Optical Model Results for Station MHS-05 Located at the Base of MBC

[139] Refer to Section 4.3 of Appendix E.
[140] Refer to Section 3.1 of Appendix G and Sections 3.5 and 4.3 of Appendix E.



Graphic 21. Comparison of COPC Concentrations in Surface Sediment to Concentrations on Particulates Suspended in Surface Water[141]

These processes, coupled with fluctuations associated with tidal movement of water, can result in variation in COPC concentrations of over an order of magnitude on routine (e.g., over the 6-hour period from high to low tide) and episodic (e.g., storm events) bases. High frequency temporal data and optical model predictions show that the cycle of particulate deposition and resuspension varies in direction and magnitude across the semi-diurnal and spring/neap tidal cycles, in response to episodic storm flows, and with seasonal changes in POC exchange from the marshes.[142]

Temporal patterns observed in analytical and modeled concentration data show that periodic rainfall events influence BCSA surface water quality in the waterways through 1) the influx of upland storm runoff and associated sediment load to the BCSA tidal zone; 2) short-term increased particulate resuspension as a result of higher velocities in the BCSA waterways during storm flows; and 3) increased downstream movement of water. These influences are most prominent in the UBC waterways, where storm runoff volumes generated during modest, relatively common storms (e.g., once monthly storms) are on par with tidal volumes.[143] Storm flows of this magnitude have been shown to result in modest (1.6- to 2.2-fold) increases in total COPC concentrations in

[141] Note: Methyl mercury was not evaluated in thin BAZ from BCC.
[142] Refer to Section 4.3 of Appendix E.
[143] Refer to Attachment G2 of Appendix G.

surface water in the UBC waterways, but have little influence on COPC concentrations in the other tidal reaches.[144]

High temporal frequency monitoring during a once-per-year magnitude storm recorded increases in particulate COPC concentrations in surface water at the downstream end of UBC by as much as 5-fold for a period of several hours during peak storm flows; but only resulted in short-term, modest (1.2 to 1.5 times) increases in particulate COPC concentrations at the downstream end of MBC (Figure 5-4), and had no notable influence on COPC concentrations at the downstream end of BCC.[145] Surface water COPC concentrations at the downstream end of the UBC main channel were observed to decline to less than half pre-storm levels for a period of several days following the peak storm flows, while post-storm average concentrations in the main channel at the base of MBC were similar to the pre-storm averages (Figure 5-4). These results demonstrate that even relatively less frequent (once per year) storm events have relatively minimal influence on surface water quality in the waterways of the lower reaches of the BCSA. Overall, these findings are consistent with other lines of evidence, such as the continuous monitoring of general water quality parameters[146], the water balance, the dye study, and the hydrodynamic and sediment transport modeling[147], all of which indicate that large storm magnitudes (e.g., once every 3 years) are necessary to notably increase waterway velocities and particulate resuspension throughout the BCSA waterway.

Major storm events, such as Hurricane Irene in August 2011 (a once in 100 year storm that resulted in 8.2 in. of rainfall in 24 hours) have a larger, short-term influence on BCSA surface water quality than the smaller, more frequent events. These storms result in both 1) increased delivery of sediment to the BCSA associated with the large volume of storm runoff and the tidal surge, and 2) elevated velocity in the main channel and in many tributaries as the large volume of uplands storm runoff drains through the system.[148] As a consequence, storms such as Hurricane Irene have the potential to result in accumulation of sediment throughout the BCSA and erosion of the waterway sediment bed in localized areas within the BCSA. A comparative analysis of channel bathymetries measured in 2014 and 2008[149] found that measurable sediment accumulation or erosion (i.e., >30 cm) had occurred in a small proportion (~9 percent) of the BCSA main channel during the 6-year period between the bathymetric surveys.[150] These changes reflect, in part, the

[144] Refer to Figure 4-9 and Section 4.3.2 of Appendix E.
[145] Refer to Section 4.3.2 of Appendix E.
[146] Refer to Section 3.1 of Appendix E.
[147] Refer to Attachments G2, G4, and Sections 2 and 3 of Appendix G.
[148] Refer to Section 3.4 of Appendix G.
[149] Refer to Section 3.2.4 of Appendix G.
[150] The majority of areas where erosion was estimated were in UBC and LBC. Due to boat access limitations, these areas were evaluated using single-beam techniques measured on transects spaced at ~100 ft. Due to the extrapolation required with this type of data set, the results for UBC and LBC are considered more uncertain than the results for

collective influences of the two hurricanes (Irene and Sandy) and of Tropical Storm Lee that occurred during that time frame. Most of the erosion was observed in isolated areas of the subtidal channel, often near where stormwater runoff enters the tidal zone from the uplands.

Tidal surges result in increased tidal influence on the BCSA (e.g., higher salinity) and increased sediment delivery from the Hackensack River estuary. Available data and hydrodynamic modeling indicate that typical surges do not result in significant increases in channel velocities in BCSA waterways and thus do not result in significant sediment resuspension.[151] These analyses suggest that storm surges are unlikely to substantially resuspension of COPCs to the water column; however, limited RI data are available to directly evaluate the influence of storm surges on BCSA surface water quality.[152] Although COPC data were collected during Hurricane Irene, which resulted in a 0.90-m tidal surge in the BCSA, the potential influences of the surge are obscured by the influences of the immense volume of storm runoff associated with the hurricane. The temporal patterns in COPC concentrations during high-frequency monitoring from September 29 to October 3, 2015, while the system was influenced by the Tropical Storm Joaquin tidal surge of 0.53 m, are generally similar to the patterns observed under spring tide conditions prior to the surge, suggesting minimal influence. However, the optical instruments were serviced from September 28–29, 2015 during the peak of the surge, so the full influence of the tropical storm is unknown.

5.2.2 Waterway-Marsh Exchange

Multiple lines of evidence (e.g., high-resolution cores, SETs, sediment transport modeling) show that the *Phragmites* marshes are highly effective at trapping suspended sediment carried into the marsh as a result of tidal flooding from the adjacent waterways.[153] As described in Sections 4.7.3 and 5.2.1, particulate deposition to and resuspension from the fluff layer at the surface of the waterway sediment bed is an important mechanism for exchange of COPCs from the waterway sediment bed to the water column and, in turn, to the marshes as surface water particulates are trapped in the marshes during tidal flooding. This process of particulate exchange and the associated net transport of COPC mass from the waterways to the marshes is observed in multiple RI data sets (e.g., characterization of near-bed particulate resuspension and deposition dynamics[154], analytical and optical-model data quantifying exchange between the marshes and waterways[155]).

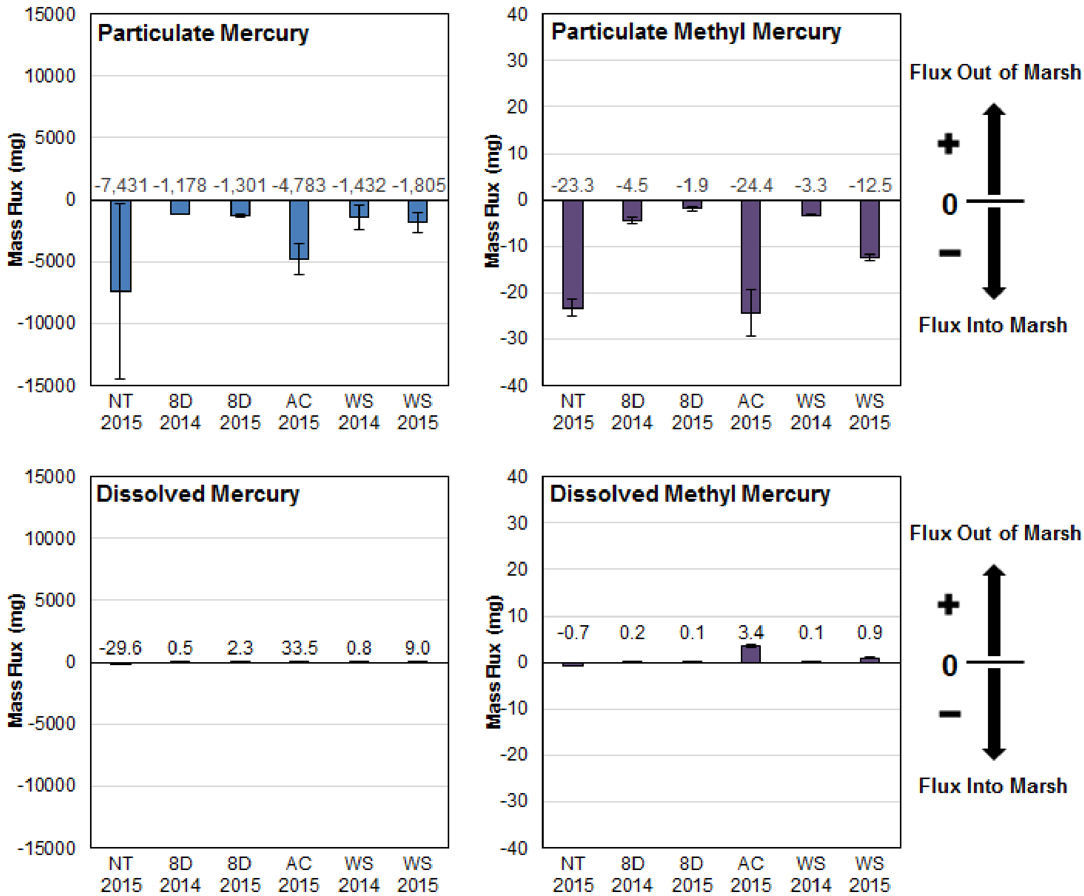
MBC and BCC for which multi-beam techniques were employed. See Section 3.2.4 and Attachment G7 of Appendix G.

[151] Refer to Section 2 of Appendix G.
[152] Refer to Section 4.3.2 of Appendix E.
[153] Refer to Attachment F1 of Appendix F and to Section 3 of Appendix G.
[154] Refer to Attachment G3 of Appendix G.
[155] Refer to Attachment E1 of Appendix E.

High temporal frequency monitoring during the 2014 and 2015 optically-based monitoring studies allowed for the calculation of mercury, methyl mercury, and PCB mass flux into and out of the marshes at several marsh tributary locations over multiple tidal cycles and site conditions.[156] The results of the monitoring demonstrated there is a net import of particulates from the waterways to the marshes, consistent with the net depositional character of the marshes. Further, particulate-bound COPCs (mercury, methyl mercury, and PCBs) were seen to be imported from the waterways to the surface of the marshes as a result of particulate trapping in the marshes during tidal flooding.[157] COPC concentrations in marsh surface sediment are influenced by the ongoing load of COPCs derived from the waterway sediment bed and reflect both the COPC concentrations in particulates accumulating on the marsh sediment surface and the low COPC concentrations in organic matter derived from the marsh vegetation. As a result, marsh surface sediment concentrations are lower than surface sediments in the waterways, but remain elevated above regional background levels (particularly in UBC and MBC; Section 5.1).

Tidal wetlands have been reported to be important sites for methyl mercury production and a potential source of methyl mercury to surrounding surface waters (Hall et. al. 2008) through surface exchange processes and marsh interflow drainage. As described in Section 4.7.2.3, interflow drainage is unlikely to be a substantial source of methyl mercury due to the small volume of drainage relative to the volume of surface water in the BCSA. Although quantification of dissolved methyl mercury fluxes during the 2014 and 2015 optically-based monitoring studies demonstrated that dissolved methyl mercury is exported from the marshes, the mass of methyl mercury exported is small relative to the volume of surface water in the system.[158] Further, the mass flux of particulate-bound methyl mercury imported to the marshes is 7 to 33 times greater than the mass flux of dissolved methyl mercury exported from the marshes. As a result, there is a strong net exchange of methyl mercury from the waterways to the marshes (Graphic 22).

[156] Refer to Section 5.3 of Appendix E.
[157] Refer to Section 5.3.3 of Appendix E.
[158] Refer to Section 5.3.3 of Appendix E.



Note: NT = Nevertouch Marsh, 8D = Eight Day Swamp, AC = Ackerman's Marsh, WS = Walden Swamp.

Graphic 22. Net Mass Flux of Particulate and Dissolved Mercury and Methyl Mercury from Waterways to the Marshes based on Optical Modeling

5.3 Biota COPCs Distribution

Mercury, methyl mercury, and PCBs have been detected in BCSA biota. General patterns of COPC distribution of the three primary COPCs by species and area sampled (BCSA reach and reference sites) are discussed below followed by a more detailed analysis of spatial and temporal variability in fish collected from the BCSA waterways. Data are presented for total mercury (analyzed in most tissues), methyl mercury, and PCBs (total Aroclors).[159,160] In most cases, the data presentations below examine patterns in COPC distribution using simple summary statistics (e.g., medians and

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[159] PCB congeners were analyzed in a subset of tissue samples and are presented in Appendix I, Attachment I2 and evaluated in the uncertainty sections of the BERA and BHHRA (Appendices L and M).

[160] All tissue data are presented as fresh weight concentrations. Median moisture content was generally in the range of 70 to 80 percent in the sampled animal matter. Median moisture in *Phragmites* ranged from ~50 percent (leaves) to ~78 percent (roots).

interquartile ranges) in tabular or graphical summaries. Statistical comparisons using Mann-Whitney U-tests, a non-parametric test, were conducted to determine statistical differences between reaches or reference sites (with a significance level of $p<0.05$).

Appendix I presents a more detailed summary of the biota COPC data. Appendix I, Attachment I3 summarizes data for other COPCs detected in biota.

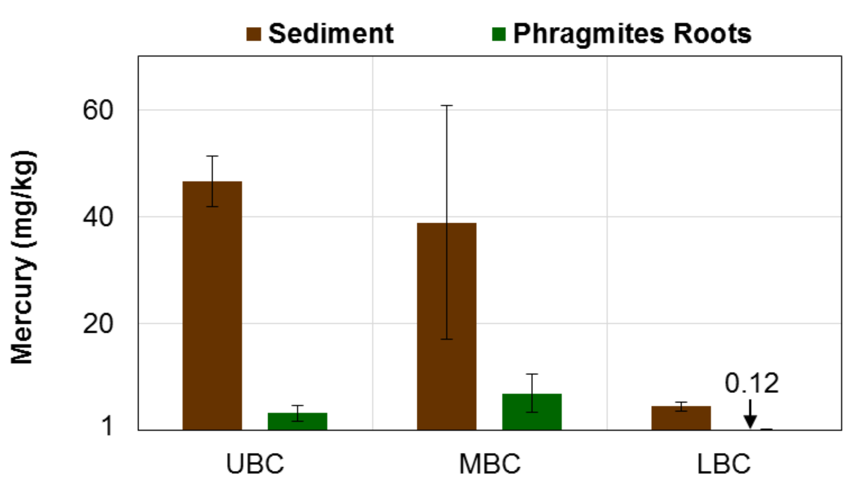
5.3.1 COPCs in Marsh Biota

COPC residues in marsh biota were sampled in *Phragmites* and marsh invertebrates.

5.3.1.1 Phragmites

Phragmites samples were collected from the root and leaves (live and dead) from individual plants, as well as the litter layer detritus that covers the marsh surface in the vicinity of the sampled plant. Overall, the data indicate that some COPC accumulation in *Phragmites* roots is occurring. COPC concentrations in roots collected from the BCSA are statistically elevated above those in reference sites in one or more BCSA reaches and generally follow concentrations found in site sediments, with higher COPC concentrations in UBC/MBC root samples compared to LBC.[161] Across all primary COPCs, root concentrations are highest for mercury.

The root COPC concentrations are a fraction of the concentrations detected in root zone sediment. For mercury, for example, the observed concentrations in the roots are in the range of ~10 to ~20 percent of that in sediments (Graphic 23).



Graphic 23 Mercury Concentrations in Sediment (Depth-Weighted Average from 0 to 30 cm) and Co-located *Phragmites* Roots

[161] Phragmites roots samples were not collected in BCC marshes.

COPCs also were detected in live leaf tissue but at concentrations lower than those in roots. The only exception to this pattern was for methyl mercury and PCBs in LBC, where the median concentrations in root and live leave tissues were similar and the concentrations in the roots were the lowest across the BCSA reaches. In the other sampled reaches—where the COPC concentrations in the roots were much higher—leaf COPC concentrations were lower than those detected in the roots, indicating little transport of COPCs from the roots to the leaves (Table 5-10).

Table 5-10. Ratio of Leaf to Root COPC Concentrations in *Phragmites* from the Upper Portion of the BCSA

	Mercury			Methyl Mercury			PCBs (Total Aroclors)		
Reach	n	Mean	SE	n	Mean	SE	n	Mean	SE
UBC	3	0.03	0.02	3	0.03	0.02	3	0.07	0.02
MBC	3	0.01	0.002	3	0.1	0.06	3	0.08	0.03

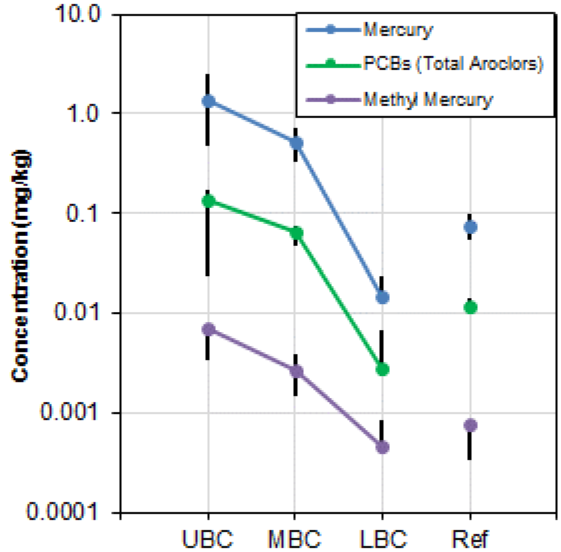
Notes: mean = arithmetic mean n = number of samples SE = standard error

This finding is consistent with the literature indicating negligible plant uptake and translocation of mercury and PCBs (Chu et al. 2006; Windham 2001; Anjum et al. 2011). Wollenberg (2005) reported mercury concentrations in Meadowlands *Phragmites* roots 10 to 1,000 times greater than in leaves and suggested that root uptake from sediment is the primary uptake mechanism for mercury in *Phragmites* and that roots are the primary storage site.

While the concentration of COPCs in leaf tissue is low, there is a pattern of increasing concentration from live leaf, to dead leaf, to detritus in the litter layer. This COPC distribution in part reflects the loss of organic matter mass as the leaves decay. Further, detritus in the litter layer is likely also influenced by sorption of contaminants from sediment depositing in the marsh and in water column by detrital material and is consistent with published literature (Windham et al. 2004) and the physical CSM for the BCSA. As discussed in Section 5.2.2, there is a net flux of COPCs from the waterways to the marshes as a result of particulate and fine-grained POC (and associated particulate-bound COPCs) transport to and retention in the marshes.

Similar to roots, there is a spatial trend to COPC levels in detritus collected from the litter layer on the marsh surface (Graphic 24). Concentrations are statistically significantly higher in the root samples from UBC and MBC than in samples from LBC, and those in LBC are lower than or similar to those in reference sites. The higher concentrations of COPCs in detritus from the upper reaches of the system correspond to the areas of the site with the highest COPC concentrations in sediment.

Collectively, *Phragmites* data indicate COPCs in that marsh sediment are not being significantly mobilized into the food web via plant uptake.



Graphic 24. COPC Concentrations in Detritus Collected from the Litter Layer of Marshes in the BCSA and Reference Sites (Median, 25th, and 75th Percentiles)

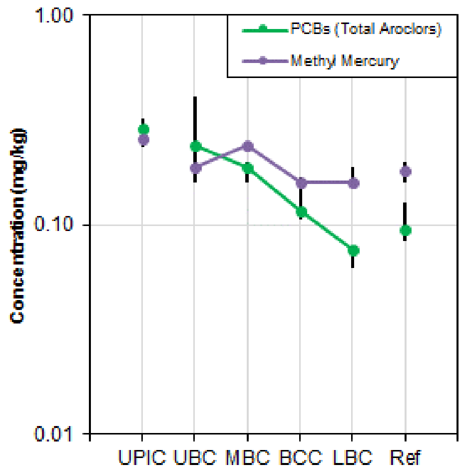
5.3.1.2 Marsh Invertebrates

Invertebrate species sampled for COPC analysis included spiders (a predator at or near the top of the marsh invertebrate food web), amphipods (primarily *Apocoruphium,* a lower trophic level invertebrate), and a variety of mixed invertebrate species (e.g., beetles, snails, centipedes occupying multiple trophic levels). In addition, earthworms (Lumbricidae.) were collected from UPIC marshes. Amphipods were not present in UPIC marshes, and earthworms were not present in the tidal zone marshes. These observations likely reflect the differences in the degree of saturation in marsh surface sediment in these settings. Marsh invertebrates were analyzed for methyl mercury and PCBs. Total mercury was not analyzed due to sample mass limitations.

Methyl mercury and PCBs were detected in all sampled taxa, but the pattern of bioaccumulation across taxa differed.[162] For methyl mercury, tissue concentrations were highest in spiders and lowest in amphipods in all marshes, as expected given trophic position. PCB concentrations were also highest in spiders, but the differences between spiders and other taxa were less distinct for PCBs than for methyl mercury. These data suggest that trophic magnification in the marsh invertebrate community is greater for methyl mercury than for PCBs, or that there is a different or supplemental source of methyl mercury (e.g., atmospheric input as shown by Tsui et al. 2012) compared to PCBs.

[162] Refer to Figure 3-5 of Appendix I.

On a spatial scale, the concentration of methyl mercury in spiders was higher in the upper reaches compared to the lower reaches (Graphic 25) but was not statistically different than that observed in the reference sites in any reach.[163] The median concentrations of PCBs in spiders were more elevated in the upper reaches than the lower reaches or in the reference sites (Graphic 25), though only the concentrations in UBC marshes were statistically elevated compared to reference sites.[164] Median concentrations of COPCs in UPIC earthworms were lower than levels measured in spiders from the same area.[165]



Graphic 25. COPC Concentrations in Spiders (Whole Body) Collected from the BCSA and Reference Sites (Median, 25th, and 75th Percentiles)

5.3.2 COPCs in Waterway Biota

COPCs were measured in composite samples of mummichog, white perch[166], fiddler crab (*Uca minax, U. pugnax*), mud crab (*Rhithropanopeus harrisii*), and shrimp (*Palaemonetes sp.*), and blue crab (*Callinectes sapidus*) from both the BCSA and reference sites. Whole body composite samples were analyzed for all species except for blue crab for which muscle and hepatopancreas tissues were analyzed. In perch, fillet samples also were collected.

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[163] Refer to Figure 3-6 of Appendix I.
[164] Refer to Figure 3-6 of Appendix I.
[165] Refer to Figure 3-5 of Appendix I.
[166] The white perch routinely sampled during the RI were perch generally in the size range of 150 to 190 mm, which is the prevalent size class in the BCSA. Larger perch (>200 mm) also were sampled and these data are presented later in this section.

COPCs were detected in waterway biota across all BCSA reaches and reference sites and in nearly every sample.[167] COPC distribution in whole body and blue crab muscle samples across species varies by COPC and by reach:

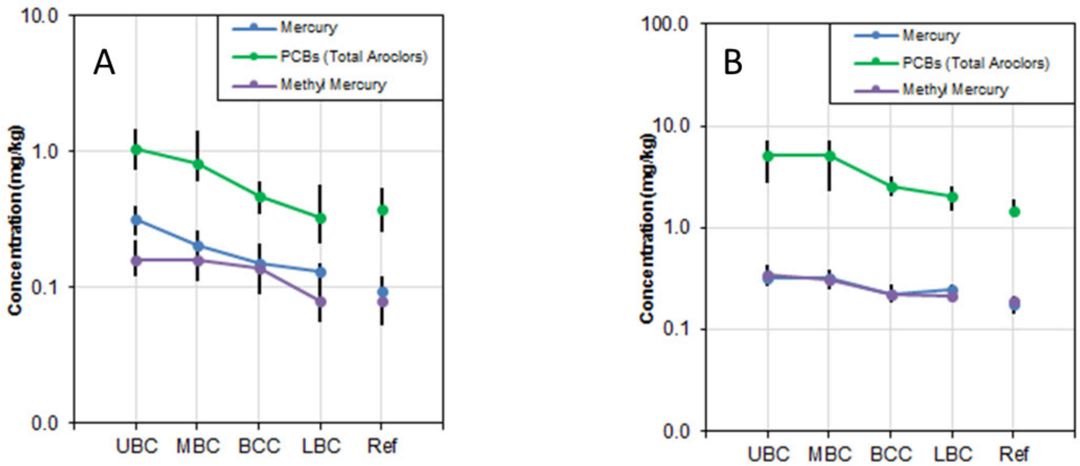
- **Mercury**. Across all reaches, the highest mercury concentrations are reported for UBC fiddler crabs and annelids. Both of these species are sediment dwellers with a high site fidelity. A pattern of higher concentrations in sediment-dwelling invertebrates in UBC is consistent with the sediment data. In other reaches, where the mercury concentrations in BAZ sediment are less, mercury tissue concentrations are greatest in white perch.

- **Methyl mercury**. Methyl mercury concentrations are highest in white perch, though median concentrations in blue crab (muscle) approach those in white perch, especially in the lower reaches of the system (BCC and LBC). Both white perch and blue crab spend a portion of their time in areas outside the BCSA, and a similarity of concentrations between the two taxa in the lower reaches could, in part, indicate the portion of the COPC body burden that is due to regional contributions. Among species that exhibit greater site fidelity, there is even less difference in methyl mercury concentrations across taxa. Across most reaches, methyl mercury concentrations in mummichog are similar to those observed in mud crab and grass shrimp.

- **PCBs**. Across all reaches, PCBs are highest in white perch and demonstrate a pattern of decreasing concentration in mummichog, mud crab, and shrimp. Fiddler crab PCB residues vary by reach but are generally in between those reported for mummichog and mud crab.

COPCs residues in white perch and blue crab likely reflect, in part, exposures that occur outside the BCSA during seasonal movement to other parts of the estuary (Section 6.3.1). COPC residues in the other sampled species reflect BCSA-specific exposures. Biota COPC concentrations display a consistent pattern of higher concentrations in the upper reaches of the BCSA compared to the lower reaches, with concentrations in the lower reaches approaching concentrations observed in reference sites. This pattern is clearly evident in fiddler crab, mummichog, and white perch (Table 5-11, Graphic 26), but less distinct for blue crab (muscle) (Table 5-12)[168].

[167] Refer to Attachment I3 of Appendix I.
[168] Refer to Figure 3-7 of Appendix I.



Graphic 26. COPC Concentrations in Mummichog (A) and Whole Body White Perch (B) (Median, 25th, and 75th Percentiles)

Table 5-11. Median COPC Concentrations in BCSA Reaches and Reference Sites

	Concentration (mg/kg wet weight)								
	Mummichog			White Perch			Fiddler Crab		
Reach	Mercury	Methyl Mercury	PCBs	Mercury	Methyl Mercury	PCBs	Mercury	Methyl Mercury	PCBs
UPIC	0.29	0.11	1.2	--	--	--	--	--	--
UBC	0.31	0.16	1.1	0.32	0.35	5.1	0.72	0.080	1.3
MBC	0.21	0.16	0.81	0.32	0.31	5.2	0.29	0.061	0.53
BCC	0.15	0.14	0.47	0.22	0.22	2.6	0.16	0.039	0.26
LBC	0.13	0.080	0.33	0.25	0.22	2.1	0.14	0.040	0.18
REF	0.095	0.079	0.38	0.18	0.19	1.5	0.092	0.027	0.24

Notes:

REF = reference site

-- = No data

All concentrations are for composited whole body samples.

White perch are for target size (150–190 mm) samples.

Across these species, COPC concentrations decline to levels not statistically different from reference site concentrations in one or more BCSA reaches (Table 5-12).[169]

[169] Refer to Figures 3-8 to 3-11 of Appendix I.

Table 5-12. BCSA Reaches with COPC Concentrations Not Significantly Different from Reference Site Concentrations[a]

Species	Mercury	Methyl Mercury	PCBs
Blue Crab (Muscle)	MBC, LBC	MBC, BCC, LBC	UBC, MBC, BCC, LBC
Fiddler Crab	BCC, LBC	BCC	BCC, LBC
Mummichog	--	LBC, UPIC	LBC
White Perch	--	BCC	--

Notes: Whole body samples, except as noted.

-- = Concentrations in all reaches are statistically elevated above reference site concentrations

Statistically significant differences determined at the $p<0.05$ level.

[a] Based on pairwise Mann−Whitney U-tests and p−value adjustment for multiple comparisons (Wright 1992).

Tissue data were collected from the BCSA and reference sites throughout the period of 2009 to 2015. Overall, COPC concentrations are variable across years and no temporal trend in tissue concentrations is apparent.[170] Temporal variability is more pronounced in the upper reaches of the system (UBC, MBC) compared to the lower reaches (BCC, LBC) and greatest for methyl mercury compared to mercury and PCBs.

Additional samples were collected to assess COPC uptake in specific tissues (perch fillet and blue crab hepatopancreas) and in larger perch (>200 mm total length) to support the risk evaluations.[171] Methyl mercury concentrations were higher in white perch fillets than in whole body, whereas PCB concentrations were lower. PCB concentrations were higher in hepatopancreas than in blue crab muscle, whereas methyl mercury was lower. Methyl mercury concentrations in large white perch (>200 mm total length) were higher than concentrations in the smaller perch (150–190 mm total length) that predominate in the BCSA and that were targeted for sampling as part of the routine site-wide monitoring. PCB concentrations in larger perch were lower compared to target-size fish.

5.4 Air COPCs Distribution

An analysis of potential atmospheric loading of COPCs to the BCSA was conducted in 2011–2012 and indicated the regional atmospheric inputs could contribute mercury, PCBs, and a variety of

[170] Refer to Attachment I4 of Appendix I.
[171] Refer to Section 3.2.3 of Appendix I.

other COPCs in the BCSA tidal zones, but were not the primary contributor to COPC loads under current conditions.[172]

In addition to deposition into the system, potential releases from the study area to the atmosphere also were assessed and sampling was conducted to evaluate the presence and magnitude of COPCs in air. Mercury was the focus of the sampling because it is present at elevated concentrations in study area surface water and sediment and because mercury in these media can be transformed into gaseous (elemental) mercury and volatilize to air in a form that can be rapidly absorbed if inhaled. PCBs were not included in the sampling because they volatilize to a lesser degree and are more likely to remain sorbed to sediment and POC. No other COPC was of concern regarding potential volatilization due to infrequent occurrence and/or low concentrations in the BCSA.

In 2011–2012, data were collected to assess total mercury in air at a potential exposure point for recreational receptors. Total mercury was monitored to specifically estimate exposure point concentrations in the breathing zone for a hypothetical kayaker. The full study and results are described in Appendix O.

Results from the 2011 multi-season study (Table 5-13) showed that, across most reaches and in most seasons, mercury concentrations in air in the BCSA are higher than those detected at the reference site but lower than that detected in the urban background locations (located upwind of the BCSA tidal zone). The data suggest that mercury concentrations vary by season, but not in a consistent manner across reaches. Mercury concentrations in air also did not vary in a consistent manner in relation to environmental factors such as wind speed, air temperatures, and light intensity.[173] Detected mercury air concentrations in all reaches except LBC were below risk-based screening levels (RBSLs).

Table 5-13. Mercury Air Monitoring Data by Sampling Date and Reach (mean/standard deviation; in ng/m^3)

Sample Date	UBC		MBC		BCC		LBC		Urban Background		Reference Site	
	Mean	StDev	Mean	StDev	Mean	StDev	Mean	StDev	Mean	StDev	Mean	StDev
Spring 2011	77	22	11	3.4	31	53	560	350	160	36	16	9.8
Summer 2011	17	11	45	10	25	6.7	200	86	88	38	12	0.58
Fall 2011	ND	ND	ND	ND	15	5.4	17	6.1	14	12	11	0.58
Spring 2012	--	--	--	--	ND	ND	13	2.5	15	1.4	ND	ND

Notes: -- = Not sampled
ND = No values detected at or above the instrument detection limit (10 ng/m^3)
StDev = standard deviation

[172] Refer to Appendix C for description of Phase 2 study and findings.
[173] Refer to Appendix O.

Mercury concentrations in UBC, MBC, and BCC were within a similar range and did not exhibit clear spatial patterns. The relatively flat air concentration pattern across UBC, MBC, and BCC does not reflect sediment and surface water mercury concentration trends, which vary considerably across these reaches (Sections 5.1 and 5.2). Low levels of mercury in air observed throughout these three reaches also is comparable to concentrations mostly at or below the instrument reporting limit at the Bellman's Creek reference site and the concentrations observed in urban background sampling.

Mercury concentrations in air were highest in LBC. The average mercury air concentration in LBC during the late spring sampling event (560 ng/m^3) exceeded the NJDEP chronic reference concentration of 300 ng/m^3. Also, eight locations at the northern end of LBC during the late spring sampling exceeded the NJDEP (2011) short-term inhalation reference concentration of 600 ng/m^3. Fourteen LBC late spring locations exceeded the NJDEP (2011) chronic inhalation reference concentration of 300 ng/m^3. In LBC, during summer 2011, four results exceeded the same chronic inhalation concentration. No other measurements exceeded NJDEP reference concentrations. No measurements study-wide exceeded the EPA industrial RBSL of 1,310 ng/m^3.

The LBC results from the seasonal sampling were further investigated in a land-based supplemental fall 2011 sampling near landfills and industrial loading sites in LBC. All results of the land-based supplemental study were below the instrument detection limit. A final monitoring event was conducted in the spring 2012 throughout the lower reaches (LBC and BCC) of the BCSA, at urban background locations, and at the Bellman's Creek reference site. All detected results were well below all RBSLs, and LBC findings from 2011 were not repeated. Mercury concentrations in the air at the reference site were below the instrument detection limit.

The elevated mercury vapor concentrations in LBC were not consistent with site data indicating the mercury concentrations in LBC surface water and sediment are lowest across the BCSA reaches. Patterns of mercury concentrations measured in air were also evaluated across seasons and with respect to both environmental parameters (light intensity, air temperature, wind) and tide stage, and no clear relationship was identified with air concentrations. Pooling data from all sampling events, mercury is present in air above concentrations reported in the reference site but below a nearby, upwind urban background location (Table 5-14). Mean concentrations across all years are below acute and chronic RBSLs and, as such, do not appear to pose a health threat.

Table 5-14. Mercury Air Concentrations by Reach across All Sample Dates (in ng/m^3)

Reach	Mean	StDev
UBC	35	33
MBC	22	17
BCC	27	59
LBC[a]	180	270
Urban Background	28	43
Reference Site	10	2.2

Notes: StDev = standard deviation

[a] LBC samples taken in spring 2011 were significantly elevated compared with other reaches and sampling seasons and unable to be replicated. Subsequent samples taken in LBC in spring 2012 fell within a comparable range with other sampling reaches.

5.5 Regional Urban Background

Data on the COPCs in the region surrounding the BCSA were compiled and analyzed.[174] The purpose of the evaluation was to determine concentrations of COPCs in the urbanized area surrounding the BCSA to support interpretation of site-specific monitoring data. These comparisons were conducted to assess the degree to which the BCSA reference sites are representative of broader regional conditions, and to aid in interpreting the significance of COPC levels in the BCSA in relation to levels found in reference sites, particularly in the lower reaches of the study area. Collectively, the analyses provide data to support evaluation of potential future risk reduction resulting under various remedial alternatives and from natural attenuation. A focus was placed on sediment and tissue data, which had more robust regional data sets than surface water.

Regional data were compiled from the Hackensack River and other nearby waterways (i.e., Newark Bay, Arthur Kill, and other Hudson-Raritan estuary locations). These regional data were then compared to RI COPC data collected from 1) the three BCSA reference sites, and 2) the lower reaches of the BCSA (LBC, BCC), where COPC concentrations are lowest and approach or are equal to those in the BCSA reference sites. Though regional contributions from the Hackensack River influence the upper reaches of the system, the concentrations in those BCSA reaches are elevated compared to reference site and regional data and were not evaluated further in this analysis.

[174] Refer to Appendix J.

Key findings of the evaluation are detailed in Appendix J and are as follows:

- **COPCs present in the BCSA also are prevalent in waterways throughout the region.** Based on the data, the COPCs measured in the BCSA and reference sites are also prevalent in the broader region surrounding the BCSA site. The COPCs evaluated as part of the regional background analysis were detected in surface water, sediment, and biological tissue throughout the urban region, typically with high frequency (i.e., >70% of all samples).

- **BCSA reference sites are representative of broader regional conditions.** COPC concentrations in the BCSA reference sites were generally similar to, and in some instances lower than, the COPC levels reported in the regional background data set.[175] In the few instances where this is not the case (methyl mercury in sediment, and mercury in blue crab hepatopancreas), median concentrations in the BCSA reference sites were lower than those in the broader region, although overall there is a great deal of overlap in COPC concentration distributions, suggesting that dissimilarities are small.

- **COPC concentrations in LBC and BCC are similar to levels in the broader region.** COPC concentrations in the lower reaches of the BCSA are similar to those reported in the regional data set. This is true, for example, for PCBs in sediment and tissue, mercury in sediments and some tissues, and TAL metals in most media sampled. As above, in the few instances where this is not the case, there typically is a large degree of overlap in COPC concentration distributions among data sets, suggesting that in most instances, the dissimilarities between the BCSA lower reaches and regional background conditions are small.

Collectively, these findings indicate that COPC concentrations in the sediments and biota of BCC and LBC, the BCSA reference sites, and regional background conditions are generally similar, and that a portion of the COPCs detected in upper reaches of the BCSA are derived from regional sources (as well as site sources). Regional background and reference conditions will be considered as one line of evidence in evaluating achievable risk reductions, establishing remedial action objectives, evaluating remedial alternatives for the BCSA, and evaluating the success of any remedial actions.

[175] Refer to Appendix J.

SECTION 6

INTEGRATIVE SITE CHARACTERIZATION

The RI analyses demonstrate that the distribution of COPCs and risk in the BCSA reflects the physical, geochemical, and biological conditions within the BCSA and interactions of the BCSA with the larger region. Twice-daily exchange with the Hackensack River, storm surges up the estuary, and baseflow and storm runoff from the surrounding uplands influence the fate of COPCs that have been deposited in the BCSA from a variety of historical industrial and other sources, and to a lesser extent, from ongoing contributions from the uplands and the estuary. The stable landscape created by the *Phragmites* marshes and the influx of sediment from the surrounding region has led to a system that is gradually recovering from past COPC discharges. Periodic redistribution of COPCs from shallow waterway sediments during storms slows the rate of natural recovery of waterway sediment and the surrounding marshes.

COPCs strongly partition to surface water suspended particulates, composed of inorganic and organic particulate material from external sources (Hackensack River, inflow from uplands) and organic detritus from the marshes. Detritus fuels the food web and, thus, provides an entry point of COPCs to biological receptors. Interaction of surface water particulates and detritus with the surface of the waterway sediment bed during routine deposition and resuspension processes appears to be important to modulating COPC uptake in biota. People consuming fish and wildlife foraging in the waterways have the highest potential exposure to site-related COPCs based on the pathways evaluated (Section 7).

A more detailed discussion follows and synthesizes the RI data into a CSM that connects the sources of COPCs to the receptors and potential exposure pathways. The CSM reflects the cumulative understanding gained by evaluation of multiple lines of evidence, including 7 years of data and site-specific and literature-based analyses.

6.1 Sources of COPCs to the BCSA Tidal Area

The BCSA and Hackensack Meadowlands have been extensively developed over the past 100+ years, resulting in a mixture of residential, commercial, industrial, and transportation uses (Section 4).[176] This development has resulted in numerous past and current sources of chemical stressors to the BCSA. In addition, up to five sewage treatment plants (STPs) discharged both conventional and non-conventional pollutants to the BCSA throughout most of the 20th century (BSAWA 1983), and CSOs still discharge to the Hackensack River. Releases from landfills constructed in marshes of LBC and Walden Swamp are an additional source of historical and

[176] Refer to Appendix B.

potentially current chemical loading to the BCSA (BSAWA 1983; Kimball & Associates 2001). Three Superfund sites, numerous other known contaminated sites, the landfills, the STPs, historical and ongoing permitted and unpermitted industrial discharges, urban runoff, and the Hackensack River all have played some role in contributing to the COPC load of the BCSA. The potential types of chemical sources to the BCSA are briefly discussed below.

6.1.1 Past Sources

Past sources of contaminant loading to the BCSA include industrial direct discharges, STP discharges, landfills, and other unpermitted discharges. This includes sources within the BCSA, as well as sources along the Hackensack River due to diurnal tidal exchange. The elevated concentrations of COPCs in subsurface sediment reflect the impacts of the historical sources to the system.

Industrial Discharges—Historical industrial activities (pre-1970s) frequently resulted in discharge of untreated or minimally treated wastewater directly to the waterway. Spills or other indirect discharges (e.g., discharge to sewers, atmospheric emissions) also may have resulted in impacts to waterways and marshes. There are three Superfund sites (Scientific Chemical Processing [SCP], Universal Oil Products [UOP], and Ventron-Velsicol) adjacent to the tidal area. Within the BCSA, there are 209 contaminated sites being addressed under New Jersey state law (e.g., Industrial Site Recovery Act; NJDEP KCS List 2015), and 137 of those sites are located south of Moonachie Avenue. Collectively, these sites represent a range of industries, including chemical production, manufacturing, warehousing, and other commercial operations. As a result, discharges from these historical industrial activities are likely to have contributed COPCs to the BCSA.

Sewage Treatment Plant Discharges— Five STPs historically discharged untreated or minimally treated sanitary and industrial wastewater directly to the BCSA. These facilities were located in MBC and UBC. In addition, indirect discharges to the tidal area came from two STPs that discharged along the West Riser Ditch upstream of the tide gate, and from the former Joint Meeting treatment plant that discharged to the Rutherford Tidal Ditch upstream of the Rutherford tide gate, in the lower reaches of the BCSA. Sewage discharges to UBC and MBC were likely at a maximum during the same period of time historical industrial COPC sources were at a maximum (1950s–1960s), providing an abundance of high organic content particulates to UBC and MBC surface water and sediment. These conditions, coupled with the longer residence time of these reaches likely contributed to the accumulation of COPCs in sediment during this period. The sewage effluent from these plants collectively contributed high biological oxygen demand and chemical oxygen demand load to the BCSA, resulting in anoxic or chronically low dissolved oxygen conditions in surface water. These conditions were documented as far back as the 1920s (NJDOH 1930). A 1982 study of priority pollutant levels at the Joint Meeting Facility found that a diverse number of chemicals were present in both the influent and effluent from the facility (NJDEP 1986).

Landfills—Four municipal solid waste landfills operated in LBC, including the Rutherford Landfill located on the northern bank of Berry's Creek, the Lyndhurst and Viola Landfills located on the southern banks of Berry's Creek, and the Avon Landfill located along the western edge of the BCSA, adjacent to the Lyndhurst Landfill. During operation, the Rutherford Landfill accepted approximately 3,000 tons of refuse per week, including domestic, industrial, and commercial debris (Malcolm Pirnie 2005). These landfills were constructed prior to restrictions regarding landfill design, use, and closure and were created by directly dumping refuse and other wastes into the marsh land. Over time, the landfill waste has sunk into the marsh, and as a consequence, waste now lies below the marsh surface and is covered by *Phragmites* in most areas. In portions of LBC, landfill waste is visibly exposed along waterway banks during low tide. RI work at the landfills identified a range of contaminants above remediation standards, including metals, PAHs, and PCBs (Kimball & Associates 2001). These landfills ceased operations between 1969 and 1975. Closure of the landfills in LBC in accordance with NJDEP regulations is underway; capping has been completed, and the leachate collection system has been constructed. Ongoing remediation is being completed in coordination with NJDEP.

Landfilling activities also historically occurred adjacent to Walden Swamp in MBC, in an area presently occupied by the NJSEA Meadowlands Sports Complex (Figure 1-2). Landfill leachate from the complex historically discharged into Berry's Creek, and a range of chemicals were measured in onsite fill, including but not limited to PCBs, PAHs, and metals (Jack McCormick and Associates, Inc. 1972, 1977).

6.1.2 Ongoing Sources

In addition to legacy effects of the historical sources identified above, ongoing inputs of COPCs from current sources contribute to the overall COPC load measured in the system. These ongoing sources include upland runoff during storm events, permitted discharges, atmospheric deposition, and regional anthropogenic contamination via exchange with the Hackensack River.

Upland Baseflow and Stormwater Runoff—The BCSA is a highly urbanized watershed, with the majority of the upland area developed for industrial, commercial, and residential use. The buildings, parking lots, roads, and other transportation infrastructure associated with urbanization create a network of impervious surfaces that do not absorb precipitation, resulting in substantial amounts of stormwater runoff. On average, 52 percent of the BCSA upland subcatchment areas consist of impervious surfaces.[177] Stormwater runoff may contribute sediments, metals, PAHs, and other COPCs (Williamson and Morrisey 2000).

The East and West Riser ditches drain more than 47 percent of the BCSA watershed and contribute sediment and COPCs to the tidal portion of the watershed. In addition, evidence of sewage has

[177] Refer to Figure 2 and Section 2.1 of Appendix D.

been observed in the East Riser Ditch during the RI. A number of other tributaries receive stormwater runoff from smaller areas of the upland, including, but not limited to: Nevertouch Creek, Eight Day Swamp Creek, PIC, Ackerman's Creek, and the Rutherford and East Rutherford ditches. Regionally, stormwater runoff has been identified as a major source of chemical and other stressors (e.g., fecal coliform, oil, and grease) into the New York-New Jersey Harbor estuary (Harbor Estuary Program 1996). However, measurements of COPC concentrations in surface water where upland runoff enters the BCSA during storm events indicates that COPC loading from this source is relatively small compared to concentrations in the tidal area.[178]

Permitted Discharges—An inventory of outfalls in the BCSA based on a visual survey of the tidal zone and an accounting of known historical and current NJPDES-permitted discharges within the BCSA is provided in Appendix G, Attachment G2. The majority of the outfalls to the BCSA are small and convey notable flow only under storm conditions. Three NJPDES-permitted outfalls have actively discharged to the BCSA since 2009: NJSEA (Permit No. NJ0023345), Meadowlands Sports Complex (Permit No. NJ0167665), and Sika Corporation (Permit No. NJ0002011). Evaluation of the permitted discharge rates confirmed that the daily discharge by these facilities comprises a small proportion of the total flows in the system.[179] The most significant flows are generated by runoff from the NJSEA sports complex, located in MBC; these flows are episodic in nature in response to collection of stormwater runoff from approximately 211 hectares (521 acres)[180] in two retention basins during storm events. Permitted industrial discharges may also contribute small amounts of a range of COPCs, but those discharges are typically monitored to ensure compliance with Surface Water Quality Standards.

Unpermitted Discharges—The BCSA field teams frequently observed oily sheens on the surface water throughout the BCSA. On several occasions these observations were reported to the EPA Remedial Project Manager and NJDEP. Follow-up to the reports did not result in the identification of the specific source(s) of the releases. Nonetheless, there are ongoing sources of petroleum and/or other chemicals (e.g., PAHs) that can impact surface water and sediment quality.

Atmospheric Deposition—Modeling of contributions to the BCSA from this source was completed as part of the Phase 2 investigation (BCSA Group 2012a), and concluded that atmospheric loading of PCBs and mercury may represent a minor source relative to the total loading of these contaminants to the BCSA. Atmospheric deposition of PCBs and mercury to the BCSA is unlikely to contribute significantly to sediment concentrations. Modeled PCB surface water concentrations from atmospheric deposition exceeded the water quality standard for the protection of human health based on accumulation of PCBs in fish tissue. The contribution of atmospheric sources to COPC concentrations in fish was not modeled, but studies by others have suggested that mercury from atmospheric deposition may be more bioavailable than mercury from

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[178] Refer to Appendix D.
[179] Refer to the BCSA water budget in Attachment G2 of Appendix G.
[180] Refer to Table 1 of Appendix D.

sediments or associated with uplands runoff (e.g., Evans et al. 2015). Isotopic tracer studies have shown that the availability of inorganic mercury introduced to soil or sediment for methylation decreases over time, in both the laboratory and the field, in its ability to be methylated due to increased binding to particulates (e.g., Hintelmann et al. 2000). In contrast, research indicates that atmospherically deposited mercury may be more readily methylated and bioaccumulated than mercury already present (Harris et al. 2007; Orihel et al. 2006, 2007, 2008). As such, atmospherically deposited mercury may be more important to bioaccumulation than mercury entering the system from other sources (Evans et al. 2015) and could be an important source of bioaccumulative mercury in the BCSA post-remedy.

Hackensack River Estuary—The BCSA receives a large volume of daily tidal input from the lower Hackensack River. The relative proportion of freshwater flow to tidal flow increases with distance from the Hackensack River (Section 4.7.2), which is consistent with the lateral gradient of decreasing salinity with distance from the river (Section 5.2, Graphic 17). Particulates from the Hackensack River account for more than 70 percent of the inorganic sediment deposited in the BCSA (Section 4, Graphic 3). Any chemicals and other stressors that are present in the lower Hackensack River water may enter Berry's Creek on the flood tide. These inputs from the Hackensack River include sewage, sediment, biological oxygen demand, chemical oxygen demand, nutrients, and COPCs (in surface water, suspended sediments, and as existing body burden in fish).

6.2 COPC Fate and Transport

The fate, transport, and bioavailability of the COPCs in the BCSA are primarily dictated by the water flow, inorganic particle transport, and the cycling of organic matter within the system. Tidal and episodic storm flows directly influence the movement of dissolved and particulate forms of COPCs in the water column, and the exchange of COPCs across tidal reaches, between the waterways and the marshes, and with the larger Hackensack River estuary. Organic matter is ubiquitous throughout the BCSA tidal zone and influences COPC fate, transport, and bioavailability both directly through COPC sorption processes and indirectly by fueling microbial processes and redox-mediated chemical reactions. These processes are described in Appendix H and are summarized below.

6.2.1 Organic Matter and Redox

COPC fate and transport in the BCSA is strongly linked to the fate of organic matter in the system. The expansive *Phragmites* marshes and the current and historical inputs of organic matter from sewage discharges have resulted in high concentrations of organic matter in BCSA sediments and surface water (Table 6-1).[181] All three of the primary COPCs strongly associate with POC[182], and POC influences the fate, transport, and bioavailability of COPCs in the BCSA. Organic matter also is a substrate for microbial metabolic processes and influences redox conditions both in the surface water column and in sediment, which, in turn, influences the chemical form of mercury and potential degradation of PCBs.[183]

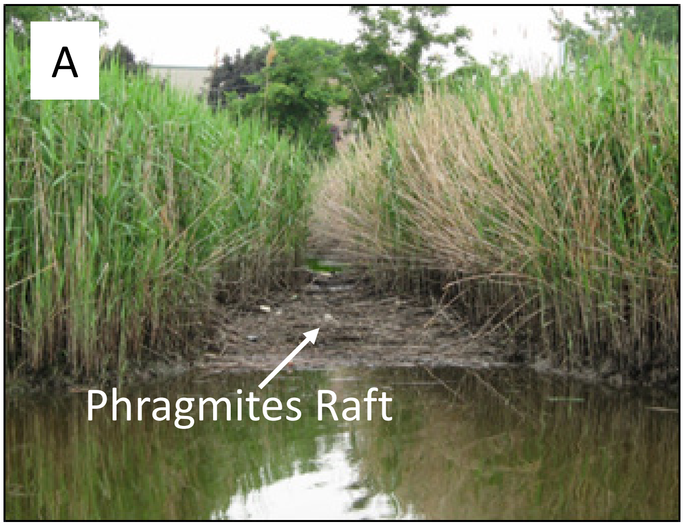
Table 6-1. Average Organic Matter Concentrations in BCSA Sediment and Suspended Particulate

Media	Average Percent Organic Matter
Waterway sediment	6
Surface water particulate	26
Marsh sediment	19

Phragmites plant material in various stages of decay, ranging from bulk stalks and leaves to fine size particulates, is visible throughout the BCSA waterways and is an ongoing source of organic matter to sediment. Senescence of above-ground plant matter supports a perennial layer of detritus (leaf litter) that covers nearly 100 percent of the marsh surface. Detritus is regularly exported from the marshes to the waterways and is visible as rafts on surface water throughout the BCSA (Graphic 27), thick mats accumulated at the bottom of the deep channels, and as layers of buried materials in waterway sediment cores and in SPI photographs (Graphic 27).[184] Breakdown of the *Phragmites* detritus provides an ongoing source of smaller size POC and dissolved organic carbon to BCSA marsh and waterway sediment, sediment porewater, and surface water (Figure 4-4). The *Phragmites* detritus also provides a substrate and nutrient source for bacteria and fungus, which decompose the material. It can also provide substrate and nutrients for other waterway and marsh fauna, such as shrimp that forage on detritus and other material.

Organic matter, principally in the form of *Phragmites* detritus (Section 4.8.3), represents a large fraction of the suspended particulate in the BCSA water column (average 26 percent) and of the unconsolidated particulates that constitute the fluff layer at the surface of the waterway sediment bed (Section 4.7.3).

[181] Refer to Section 3.5 of Appendix E and Section 3.2 of Appendix F.
[182] Refer to Section 4.1 of Appendix E.
[183] Refer to Section 2 of Appendix H.
[184] Refer to Section 2 of Appendix F.



Graphic 27. Large Particulate Organic Matter (Stems, Leaves) from *Phragmites* Accumulated in a BCSA Tributary (A) and Observed at the Waterway Sediment Bed Surface during the SPI Study (B)

The abundant supply of labile carbon in BCSA sediment fuels microbial activity and growth, which is higher in the summer. As labile organic carbon is metabolized, dissolved oxygen in sediment porewater is consumed. Because the supply of oxygen to sediment porewater is limited by several factors (e.g., low solubility of oxygen in water, slow rates of diffusion), oxygen is typically depleted at relatively shallow depth in sediment systems such as the BCSA where organic carbon is abundant (Howes et al. 1984) and microbial respiration shifts to alternative electron acceptors (e.g., iron, manganese, sulfate) that are less energetic (Stumm and Morgan 1981). The result is a vertically stratified profile of redox conditions oriented around the hierarchy of available electron acceptors to support microbial respiration. As is described below, these redox conditions have important implications for COPC fate, transport, and bioavailability—most notably mercury complexation, methylation, and demethylation.

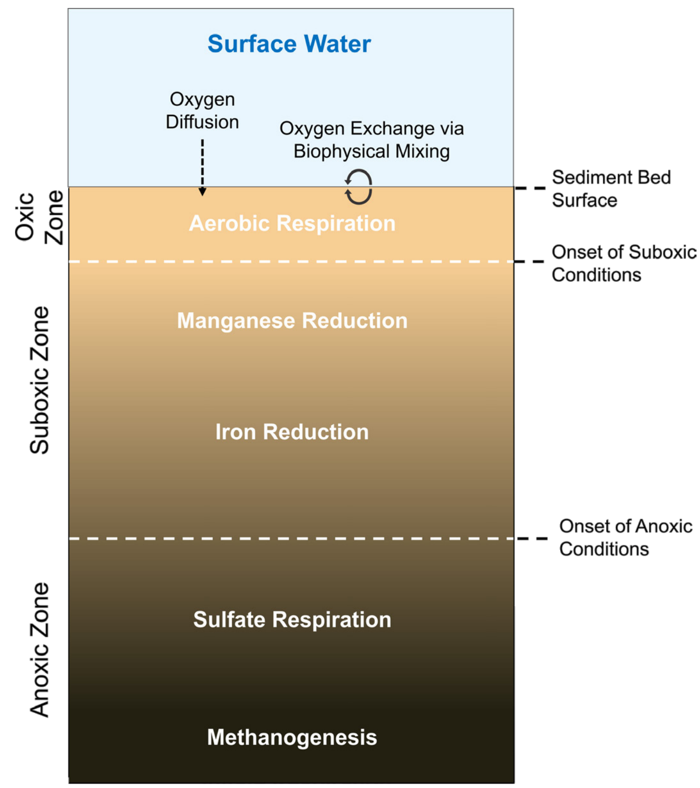
Broadly, the sediment redox profile consists of three general zones (Graphic 28):

- **Oxic Zone:** The oxic zone is the most surficial zone where oxygen is present and aerobic respiration is the dominant terminal electron acceptor process.

- **Suboxic Zone:** The suboxic zone underlies the oxic zone and is characterized by depleted levels of dissolved oxygen, where respiration shifts to reduction of nitrate, manganese, and iron.

- **Anoxic Zone:** The anoxic zone occurs below the suboxic zone and is characterized by absence of oxygen and by anaerobic metabolism through sulfate reduction and methanogenesis.

The development of sediment redox profiles is dependent on the abundance and distribution of labile organic carbon and electron acceptors. BCSA waterway sediment is characterized by thin oxic (<1 cm) and suboxic (<5.8 cm) zones.[185] A large portion (approximately 62 percent) of the main channel is subtidal (Figure 4-2) and sediment in these areas is perpetually saturated. While sediment in the intertidal mudflats and tributaries is routinely exposed at low tide, the sediment in these regions is predominantly fine-grained and poorly drained.



Graphic 28. Illustration of Redox Stratification in Sediments

Marsh sediment exhibits greater spatial and temporal variability in redox zonation and a generally thicker oxic zone and deeper onset of suboxic and anoxic conditions, than waterway sediment.[186] The large percentage of macroporous materials in the marsh root zone allows for a greater degree of tidal water exchange of near-surface (e.g., top 15 cm) marsh sediment relative to waterway sediment—particularly in near-bank areas of the marsh where, during low tide periods, interstitial sediment porewater can drain from the near-surface marsh root zone via the interflow processes

[185] Refer to Section 4.1 of Appendix F.
[186] Refer to Section 4.1 of Appendix F.

(Section 4.7.2.3).[187] In turn, the near-surface sediment from which the porewater had drained is subsequently resaturated on the following high tide, delivering a fresh supply of dissolved oxygen to the sediment. This routine saturation/de-saturation of near-surface marsh sediment in near-bank areas of the marsh, coupled with the abundant supply of relatively labile organic matter, results in a dynamic redox environment that fluctuates between oxidizing and reducing conditions within this shallow zone of marsh sediment.

The marsh sediment redox profile is also influenced by the *Phragmites* plants, which translocate oxygen from the atmosphere and express it in the root zone—contributing to the thicker oxic and suboxic zones in marsh sediment relative to waterway sediment. Further, manganese concentrations in marsh surface sediment are elevated in UBC and, to a lesser extent, MBC compared to marsh surface sediment in BCC and MBC, and to waterway surface sediment system-wide.[188] Because manganese has a higher energy yield as an electron acceptor than sulfate, the greater relative abundance of manganese likely results in sulfate reduction being less favored near the marsh surface, effectively pushing anoxic conditions deeper into the vertical profile.

Collectively, these processes contribute to a generally deeper and more varied distribution of methyl mercury in marsh sediment compared to waterway sediment.

6.2.2 Chemical Partitioning and Transformation

The distribution, fate, and transport of chemicals in an estuarine environment such as the BCSA are directly influenced by chemical partitioning and transformation reactions/processes that dictate the form (e.g., aqueous versus particulate, chemical species) of the chemical present. As described in Appendix H, chemicals partition between the aqueous and particulate phases in the water column and in the sediment bed as a result of chemical adsorption/desorption, ion exchange, and precipitation/dissolution reactions (Di Toro et al. 1991; Lewis and Landing 1992). Partitioning between these various phases is governed by a complex interplay of physio-chemical processes, many of which are reversible and respond to variations in water and sediment chemistry. Chemical partitioning not only has important implications for COPC fate and transport (Section 6.2.3), it also can have important implications regarding COPC bioavailability as particle-bound chemicals are generally less bioavailable than free chemicals in the aqueous phase (Landrum et al. 1985; Black and McCarthy 1988; USEPA 1998).

6.2.2.1 Mercury and Methyl Mercury

Mercury can be present in several inorganic and organic forms in natural systems, and its distribution among these forms is dependent on a multitude of factors. Most commonly, mercury

[187] Refer to Section 5.1 of Appendix E.
[188] Refer to Section 4.1 of Appendix F.

is present as mercuric salts and organomercuric (methylated) compounds (Morel et al. 1998). One of the organomercuric compounds, methyl mercury, is the most bioaccumlative and toxic form of mercury. Thus, understanding the processes that influence net mercury methylation is critical to understanding potential mercury biouptake.

Mercury and methyl mercury have a strong affinity for organic matter (Hollweg et al. 2009) and strongly partition to the particulate phase (Figure 6-1). Particulates and POC play a prominent role in the distribution of mercury and methyl mercury in the BCSA.[189] On average, 96 and 78 percent of mercury and methyl mercury, respectively, in surface water samples are bound to particulates, and preferentially accumulate in the fine-grained sediment that is high in organic matter content (Hollweg et al. 2009).

Methyl mercury concentrations in the environment reflect a balance of methylating and demethylating processes (Figure 6-1), as well as exchange of methyl mercury among media (e.g., sediment to water to air). Mercury methylation is primarily mediated by microbial activity that is favored in anaerobic conditions and, thus, occurs mostly in sediment (Ullrich et al. 2001). Research suggests that mercury methylation capability is present in a diverse group of microorganisms (Parks et al. 2013; Gilmour et al. 2013; Bae et al. 2014; Schaefer et al. 2014). Sulfate-reducing bacteria are likely to be a prominent methylating microbial population in the environment (Compeau and Bartha 1985; King et al. 2000; Gilmour et al. 2013), although iron-reducing bacteria (Warner et al. 2003; Fleming et al. 2006; Kerin et al. 2006) and methanogenic populations (Hamelin et al. 2011) have also been reported to methylate mercury. Peak methyl mercury production rates most typically occur at the onset of sulfate reduction (Hong et al. 2014; Eckley and Hintelmann 2006) (i.e., at the intersection of the suboxic and anoxic zones shown in Graphic 28).

The highest methyl mercury concentrations are most often seen in the surface (0–2 cm) increment of BCSA waterway sediment cores, and concentrations typically decrease sharply to relatively low levels at depths below the top 2 cm of waterway sediment (Graphic 16). This observation is consistent with the shallow depth at which the onset of anoxic conditions occurs in waterway sediment based on both voltammetry measurements as well as visual observations of the sediment.[190] The vertical profile of methyl mercury concentrations in marsh sediment typically shows more elevated concentrations across a depth range of 10 to 20 cm below the marsh surface, without a distinct peak in concentration. These patterns reflect the more dynamic redox environment of the near-surface marsh sediment (compared to waterway sediment) and the

[189] Refer to Appendices E and F and to Figure 4-2 of Appendix E.
[190] Refer to Sections 2 and 4.1 of Appendix F.

fluctuation of the depth of onset of sulfate reducing conditions in response to tidal flooding and other processes (Section 6.2.1).[191]

Net methyl mercury production is, in part, dependent on the availability of free, dissolved-phase, bioavailable inorganic mercury in porewater; thus, association of mercury with the particulate phase is an important factor influencing methyl mercury concentrations in sediment and, in turn, the overall bioavailability of mercury in aquatic systems (Ullrich et al. 2001; Hsu-Kim et al. 2013). Inorganic partitioning to the particulate phase is primarily driven by formation of minimally soluble sulfide mineral phases and sorption to POC.[192] The high sulfide and organic matter content of the waterway and marsh sediments provides a high capacity for the sediments to sequester mercury (Hammerschmidt and Fitzgerald 2004; Chen et al. 2009), which reduces mercury availability to microbes for methylation (Barkay et al. 1997) and potentially limits the bioavailability to other ecological receptors (Chen et al. 2009). Sediment chemical analyses during the RI have documented high concentrations of AVS in both waterway and marsh sediments of the BCSA.[193] The bulk of the inorganic mercury in BCSA sediment is composed of highly unavailable inorganic mercury bound in sulfide/sulfhydryl complexes (e.g., cinnabar, metacinnabar, or organic matter containing thiol-type functional groups).[194] A number of studies have documented the low availability of these types of mercury species for methylation (Hsu and Sedlak 2003; Ravichandran 2004). Overall, the site geochemistry is conducive to conditions of reduced mercury availability for microbial methylation, which limits the concentrations of methyl mercury present in BCSA abiotic media. In addition, other researchers have documented high rates of mercury demethylation in BCSA sediments (Cardona-Marek et al. 2007).

The decrease in percentage of methyl mercury from BCC and LBC to MBC and UBC (Graphic 15) is consistent with the generally higher levels of AVS in the upper reaches. It is also reflected in the higher proportion of inorganic mercury associated with the less available fractions during selective sequential extraction (SSE) analysis of samples from MBC and, in particular, UBC compared to samples in the lower reaches (Graphic 29).[195] The inverse relationship of inorganic mercury concentration to inorganic mercury throughout the BCSA is reflected by the fact that the slope of decreasing concentration gradient in sediment from north to south for methyl mercury is significantly shallower than that observed for mercury (Graphic 13). This also is likely the reason that methyl mercury in fish tissue decreases less from north to south than does total mercury (see Section 5.3.2 and Graphic 26).

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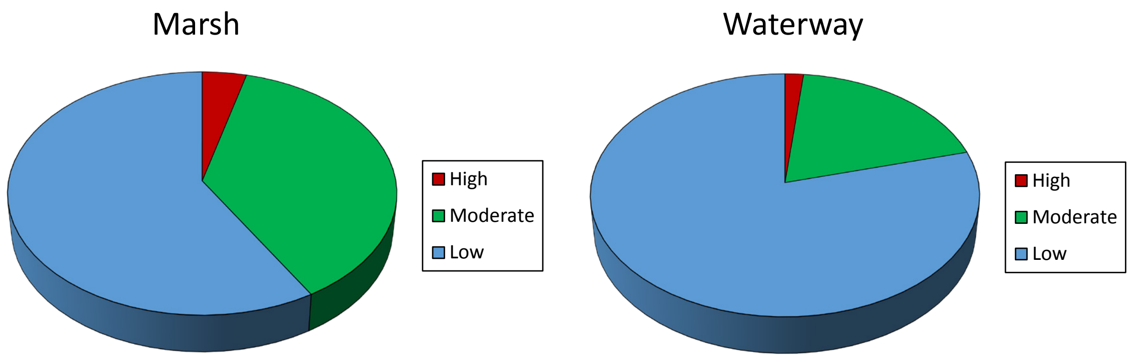
[191] Refer to Section 4.1 of Appendix F.
[192] Refer to Section 4 of Appendix F and Section 2.4 of Appendix H.
[193] Refer to Section 4.2 of Appendix F.
[194] Refer to Section 4.5 and Attachment F11 of Appendix F.
[195] Refer to Section 4.5 of Appendix F.



Graphic 29. Average Distribution of Low, Moderate, and High Bioavailability Fractions of Mercury in Marsh and Waterway Surface Sediments Based on Sequential Extraction[196]

The net depositional setting of the BCSA has led to burial of historical peak mercury concentrations to depths well below the surface of the sediment bed (Graphic 14), thereby limiting potential for exposure and transport. This is particularly true in the marshes, which consistently show substantially lower mercury concentrations in surface sediment relative to peak concentrations in the subsurface. Waterway cores show greater variability in the mercury profiles, reflecting the higher energy environment of these morphologies and the influence of episodic storm disturbances. Despite the variability in waterway mercury concentration profiles, the majority of waterway high-resolution cores show a substantial decrease in mercury concentrations from historical peaks at depth to the concentrations at the surface. Additionally, peak mercury concentrations occur well below the depth of peak mercury methylation, which typically occurs in the top 2 cm of waterway sediment (Graphic 16).

The age of the sediment increases with depth in the net depositional setting of the BCSA. As sediments age, the structure of the organic matter changes and COPCs associated with it become more tightly bound (Swindoll et al. 2000). Similarly, over time, minerals such as HgS transition from more amorphous, reactive forms to more crystalline forms that are less reactive (NRC 2003). These sediment diagenesis processes result in increased sequestration of mercury, reduced availability of mercury for methylation, and reduced mercury bioavailability to higher trophic levels (Hatzinger and Alexander 1995; Swindoll et al. 2000; NRC 2003).

These physical and chemical processes combine in the BCSA to strongly sequester inorganic mercury and render a large portion of inorganic mercury unavailable for methylation and biouptake.

[196] High bioavailability are the F1 and F2 SSE fractions, moderate bioavailability is the F3 SSE fraction, and low bioavailability is the F4 and F5 SSE fractions (Refer to Appendix F, Section 4.5).

6.2.2.2 Polychlorinated Biphenyls

PCBs principally associate with the particulate phase in the water column and with bedded sediment (NRC 2001) due to their highly hydrophobic character (log K_{ow} of 4.5–8.2, Hawker and Connell 1988) and strong affinity for organic matter (log K_{oc} 3.5–6.2; Schwarzenbach et al. 2005). These characteristics are reflected by the distribution and persistence of PCBs in the environment and in BCSA sediments (Figure 6-2). The vast majority of PCB mass is associated with bedded sediment, and, on average, 86 percent of the PCB mass in surface water samples is associated with suspended particulates.[197]

Although PCBs are generally recalcitrant, they have been shown to degrade in the environment through reductive dechlorination (Berkaw et al. 1996) and biological degradation processes (Abramowicz 1990; Bedard and Quensen III 1995). Generally, the "lighter" Aroclors (e.g., 1016, 1242, and 1248) composed of less-chlorinated congeners are more water soluble and, thus, more susceptible to volatilization and degradation than the more-chlorinated PCB congeners (NRC 2001). The more highly chlorinated PCBs are more strongly sorbed to particulate matter, and are more resistant to degradation and volatilization (NRC 2001). As a result, PCBs in sediment generally become enriched in the more-chlorinated congeners over time.

The resistance of PCBs to degradation processes is, in part, due to the limited availability of PCBs in the dissolved phase for chemical reaction and microbially mediated processes. Adsorption of PCBs to sediment can greatly reduce the rate of degradation (Loganathan and Lam 2011). PCBs in the aqueous phase are predominantly associated with suspended particulate.[198] The limited solubility of PCBs is consistent with the persistence and long-term burial of PCB mass within the high organic content sediment of the BCSA.

In general, abiotic transformation processes, such as hydrolysis, oxidation, and photolysis do not result in significant degradation of PCBs in water (Callahan 1979; NRC 2001). Overall, PCB degradation is a very slow process (Sinkkonen and Paasivirta 2000).

The net depositional setting of the BCSA has led to burial of historical peak PCB concentrations within the site sediment to depths below the sediment surface where potential for biological exposure and transport is greatest (Graphic 14). Across all morphologies in the BSCA tidal zone, maximum PCB concentrations in sediment occur at depth in the majority of locations sampled. This is particularly true of cores in the marshes, which consistently show lower PCB

[197] The remaining 14 percent is the fraction of PCBs detected in filtered samples. These detections were generally at low concentration (typically within 10x of the detection limit). Because of the hydrophobic nature of PCBs, it is likely that these PCBs are bound to colloids small then 0.45 µm in size; however, this has not been verified at the BCSA site.
[198] Refer to Section 4 of Appendix E.

concentrations in surface sediment relative to peak concentrations in the subsurface.[199] Waterway cores show greater variability in the PCB profiles, reflecting the higher energy environment of these morphologies and the influence of episodic storm disturbances. Despite the variability in PCB concentration profiles, 92 percent of the of waterway high resolution cores show a substantial decrease in PCB concentrations from historical peaks at depth to the concentrations at the surface.[200] Exceptions to this generally occur at locations in the waterways subject to episodic higher energy, such as areas where upland stormwater enters the tidal zone and meander bends in the main channel.

Biouptake of PCBs can occur in pelagic and benthic organisms through adsorption from water and ingestion of prey or particulate matter (in the sediment bed or the water column) (Arnot and Gobas 2004). The freely dissolved fraction of PCBs is the most bioavailable fraction to these organisms (Di Toro et al. 1991; USEPA 2012). Many studies have shown that strong partitioning of PCBs to particulate and colloidal organic matter in porewater and surface water reduces their availability for biouptake (Di Toro et al. 1991; Luthy et al. 1997; NRC 2003; Reichenberg and Mayer 2006; USEPA 2012). Thus, it is likely that the high levels of POC in BSCA act to limit the fraction of PCBs that is available for biouptake and trophic transfer up the food chain.

PCBs associated with organic matter become more tightly bound as sediment ages and the structure of the organic matter changes (Swindoll et al. 2000). These sediment diagenesis processes result in increased sequestration and reduced bioavailability of PCBs over time (Hatzinger and Alexander 1995; Luthy et al. 1997; Alexander 2000; Swindoll et al. 2000; NRC 2003). Several mechanisms have been proposed for the evident decrease in highly chlorinated organic compound bioavailability in sediments with time, including the encapsulation of organic matter by mineral phases and the slow diffusion of highly chlorinated organic compounds to less accessible sorption sites in more condensed forms of organic matter (Luthy et al. 1997; Cornelissen et al. 2005). Also, with time, the more available PCB fractions will be slowly lost to biotic and abiotic degradation processes, and sediments will become enriched in less bioavailable PCBs.

These physical and chemical processes combine in the BCSA to strongly sequester PCBs and render a large portion unavailable for biouptake.

6.2.3 COPC Transport

Advection and dispersion in response to tidal flow and episodic storm flows are the primary mechanisms for particulate- and dissolved-phase COPC transport in the BCSA.[201] Mercury,

[199] Refer to Attachment F1 of Appendix F.
[200] Refer to Table 2b of Attachment F1, Appendix F.
[201] Refer to Section 3 of Appendix H.

methyl mercury, and PCBs all preferentially associate with organic matter; therefore, the fate and transport of these COPCs is closely tied to that of POC and DOC in the system.

The following presents a summary of the important physical processes that influence COPC fate and transport in the BCSA based in large part on the analyses presented in Appendix D (Urban Hydrology), Appendix E (Surface Water Characterization), and Appendix G (Hydrodynamics and Sediment Transport).

6.2.3.1 Advection and Dispersion

Water flow and associated sediment transport are the dominant mechanisms by which chemicals move through the BCSA. The vast majority of the time (i.e., except during large storms that occur on average once every 1 to 5 years or less frequently)[202] flow in the BCSA is tidally dominated (Section 4.7.2). Tidal water flows into and out of the BCSA twice a day, and COPC transport is principally facilitated by tidally driven advection and dispersion. Lower portions of the site (LBC, BCC) routinely exchange water with the Hackensack River estuary and are characterized by water quality that resembles that of the larger estuary (Section 5.2).[203] Conversely, there is less frequent exchange between UBC and MBC and the estuary, and water quality in these reaches strongly reflects local conditions and the influences of fluff layer interactions with the surface of the waterway sediment bed.

Temporal patterns in BCSA surface water quality and COPC concentrations reflect solute and particulate transport in response to tidal and storm flow conditions.[204] A tidally dependent, oscillating pattern of salinity is observed throughout the BCSA. Salinity levels peak at high tide and are at a minimum at low tide, as the result of tidal movement of water back and forth in the system (Graphic 30). The primary COPCs exhibit an inverse of this pattern, as higher-COPC-concentration water moves downstream during ebb tide and lower-COPC-concentration water moves upstream during flood tide (Graphic 30).

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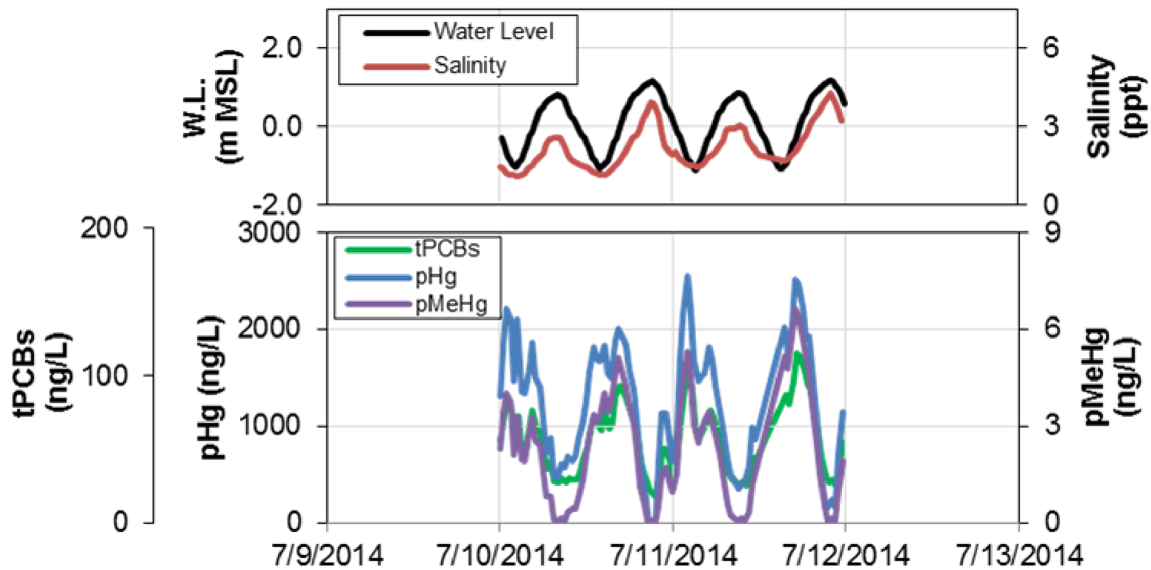
[202] The once per year (2.7 in. in 24 hours) event is estimated to produce a storm runoff volume approximately equivalent to the average neap tidal prism. The once per 5 year (4.2 in. in 24 hours) event is estimated to produce a storm runoff volume approximately equivalent to the average spring tidal prism.
[203] Refer to Section 3 of Appendix G and Sections 3 and 4 of Appendix E.
[204] Refer to Sections 3.5 and 4.3 of Appendix E.



Graphic 30. Typical Tidal Variation in Salinity and COPC Concentrations Observed at MHS-05 (Southern End of MBC)

Episodic storm events result in a short-term alteration in the tidally dominant flow conditions in the BCSA and affect chemical transport in the system.[205] The influence of storm events is strongest in UBC, which receives runoff from more than 59 percent of the upland watershed.[206] Relatively frequent storm events (e.g., once per month to once per year) increase downstream movement of water relative to typical, non-storm flow conditions, and water quality in UBC can approach that of the freshwater storm runoff (low salinity and relatively low COPC concentrations) for a period of several days following a storm (Section 4.7.2). Much larger, less frequent (once every 1 to 5 years)[207] storm events are predicted to be necessary for a similar influence to be seen through the entire length of the BCSA main channel.

6.2.3.2 Particle Exchange between Sediment and Surface Water

The majority of COPCs in the BCSA are principally associated with the particulate phase in BCSA sediment and surface water. As a result, particulate-phase exchange and transport processes are important with respect to chemical fate and transport in the BCSA. The majority of particulate-phase transport occurs as a result of the particulate resuspension and deposition processes. Particulates and particulate-bound COPCs are exchanged between the waterway sediment bed and surface water as a result of fluff layer particulate resuspension and deposition processes primarily

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[205] Refer to Section 3 of Appendix G and Section 4.3 of Appendix E.
[206] Refer to Appendix D, Table 1.
[207] The once per year (2.7 in. in 24 hours) event is estimated to produce a storm runoff volume approximately equivalent to the average neap tidal prism. The once per 5 year (4.2 in. in 24 hours) event is estimated to produce a storm runoff volume approximately equivalent to the average spring tidal prism.

driven by tidal and episodic storm flows (Sections 4.7.2.2 and 5.2.1), although other processes also can also play a role (e.g., wind-driven waves along mudflats, direct rainfall to intertidal mudflat and tributary sediment at low tide, prop wash, and bioturbation).

High-frequency monitoring at the BCSA has shown that, under typical site conditions, COPC exchange from bedded sediment to surface water is mediated by particulate exchange from the fluff layer (Section 5.2.1, Graphic 20). In turn, surface water particulates and associated COPCs are transported by water movement in the system. Therefore, fluff layer interaction is a mechanism for redistribution of COPCs from high concentration areas of waterway surface sediment to other areas in the system. Optically-based monitoring and other lines of evidence show that particulates and particulate-phase COPCs are carried into and retained in the marshes with each tidal flooding event.[208] As a result, marsh surface COPC concentrations reflect the particulate COPC concentrations in surface water in the vicinity of the marsh, and the contribution of relatively clean organic matter input from marsh vegetation. Storm runoff events can result in a short-term increase in fluff resuspension in the waterways of the upper reaches and associated downstream transport; however, monitoring indicates that influences of these storm flows on COPC concentrations in surface water in the lower reaches is minimal, even during a once-per-year magnitude storm event (Section 5.2.1).

Under typical conditions, channel velocities and associated shear stresses are insufficient to resuspend waterway bedded sediment below the fluff layer (~0.5 cm).[209] Storm flows associated with large, infrequent (e.g., once every 3 or more years) storm events are necessary to produce the range of elevated channel velocities during the short duration of the storm flow that may result in erosion of near-surface (estimated to be typically on the order of a few centimeters) bedded sediment in localized areas of the waterway. Influences of storms are most prominent in the upper reaches where a large amount of the upland storm flows enter the BCSA. For example, 59 percent of the upland watershed drains into the UBC. Infrequent major storms, such as Hurricane Irene (a once in 100 years storm event), can result in elevated channel velocities and deeper (on the order of 10+ cm) erosion of the sediment bed in localized areas of the waterway (e.g., at meander bends, deep channel areas).[210] Bathymetric analysis indicates that these types of movement can potentially occur in approximately 6 percent of the total waterway area, in locations where such impacts would be expected (near bridge abutments, sharp bends, sharp meanders, entry points of upland storm discharges, deep subtidal channel areas).[211] Tidal surges associated with rare major storm events, such as Hurricane Sandy (a once in 500+ year flood event), are likely to result in a large, short-term increase in sediment loading to the BCSA. Despite the short-term perturbations introduced by these infrequent storm events, the multiple lines of evidence collected during the RI

[208] Refer to Section 5 of Appendix E.
[209] Refer to Section 3.5 of Appendix G.
[210] Refer to Section 3.4 of Appendix G.
[211] Refer to Section 3.2.4 of Appendix G.

show that the BCSA supports a long-term stable morphology and net accumulation of sediment except in a few localized areas. Ongoing sediment deposition is resulting in a trajectory of natural recovery of site sediment throughout the marshes and a majority of the waterways (Section 6.5).

The morphologic character and dense vegetation of the marshes act to buffer flow energy, and velocities in the marshes are insufficient to resuspend deposited sediment, even during major storm events such as Hurricane Irene.[212] COPCs associated with sediment in the marshes are buried over time by ongoing sedimentation and detrital deposition from the highly productive overlying foliage (Section 6.5).[213] COPCs bound to particulates deposited in the marshes are unlikely to be remobilized due to the low-energy conditions in the marsh and the physical trapping of particulates by the vegetation (e.g., root mat, leaf litter).[214] However, transport of particulate COPCs from waterway sediment to the marshes as a result of fluff layer resuspension and transport slows the recovery of the marshes.

6.2.3.3 Dissolved Exchange between Sediment and Surface Water

Other sediment-surface water exchange processes, such as diffusion and groundwater advection, are of limited importance relative to particulate interactions between the sediment bed and surface water column. Diffusion is a rate-limited process that is slow compared to the surface water residence times (less than 1 week) for Berry's Creek. Groundwater discharge to the BCSA tidal zone is limited by the area geology and the ubiquitous presence of low-permeability clays at a shallow depth beneath the tidal zone (Section 4).[215] As a result, COPC transport to the water column with groundwater discharge and/or mobilization from sediment porewater due to upwelling is not significant. However, these processes may be important in facilitating exchange of COPCs from waterway bedded surface sediments to the fluff layer particulates, and thus indirectly important to COPC exchange to the water column.

6.2.3.4 Marsh Interflow

Interflow from BCSA marshes was determined to be of limited importance relative to particulate interactions between the sediment bed and surface water column (Section 5.2.2). Interstitial water drains as interflow from near-surface sediment in the *Phragmites* root zone along bank areas of BCSA marshes to adjacent tidal waterways in response to tidal inundation and bank infiltration processes.[216] Samples collected during the RI indicate that, in some locations, marsh porewater can contain elevated levels of dissolved methyl mercury relative to surface water; thus, interflow

[212] Refer to Section 3.5 of Appendix G.
[213] Refer to Attachment F1 of Appendix F.
[214] Refer to Section 3.5 of Appendix G.
[215] Refer to Sections 2.3 and 2.4 of Appendix D.
[216] Refer to Section 5 of Appendix E.

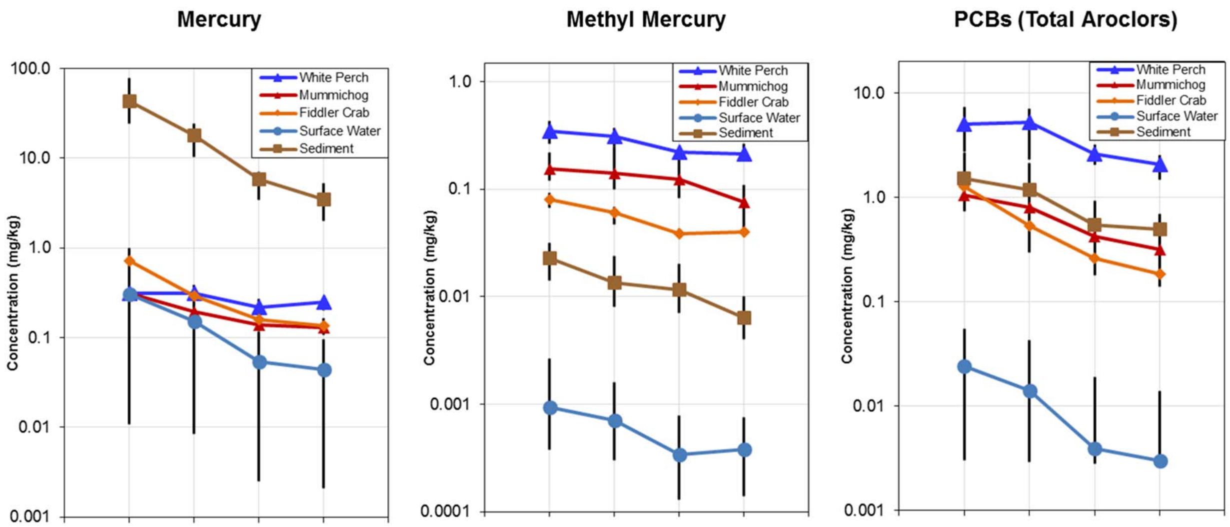
represents a potential pathway for transport of methyl mercury from BCSA marshes to surface water.[217] Sampling of marsh porewater and interflow seepage confirmed that concentrations of dissolved mercury and PCBs are very low in interflow, and thus are not transported to a substantive degree via marsh interflow. This was as expected because of their strong affinity for the particulate phase and POC.

Hydrologic analyses of marsh sediment properties show that contributions of interflow to surface water quality in the BCSA are limited by the small volume of interflow (0.00002 to 0.2 percent) relative to the tidal volume in the system.[218] High frequency, optically-based monitoring of several marsh tributaries demonstrated very limited net transport of dissolved methyl mercury from the marshes to the waterways as a result of interflow drainage and surface exchange processes.[219] The mass of dissolved methyl mercury exported from the marshes during these studies was found to be 7 to 33 times less than the mass of particulate methyl mercury imported to the marshes due to particulate deposition and accumulation during tidal flooding (Graphic 22). Optical monitoring demonstrated that the mass of dissolved mercury exported from the marshes during tidal flooding was more than 2 orders of magnitude less than the mass of particulate mercury imported to the marshes.

6.3 COPC Biouptake

BCSA biota show a consistent trend of decreasing concentrations from the upper reaches to the lower reaches. This pattern in seen in all biota except blue crab, and parallels the COPC trends in waterway and marsh sediment.[220] When tracked across the BCSA reaches, changes in COPC concentrations in waterway biota clearly parallel those in sediment, and those in surface water parallel those in sediment (Graphic 31).

[217] Refer to Section 5 of Appendix E and Section 5 of Appendix F.
[218] Refer to Section 5.2 of Appendix E.
[219] Refer to Section 5.3.3 of Appendix E.
[220] Refer to Figure 4-1 of Appendix I.

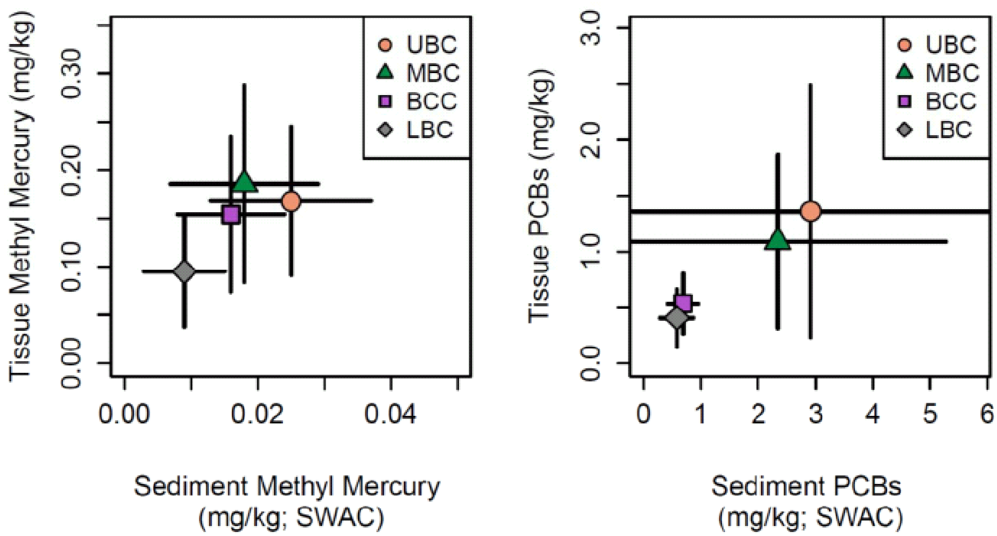


Graphic 31. COPC Concentrations in Select Biota, Surface Water and BAZ Surface Sediment (Median, 25th and 75th Percentiles) by BCSA Reach

6.3.1 Waterway Biota

Overall, there is a strong relationship between COPC levels in sediment and biota over a broad scale. When data are pooled by reach, and mean concentrations in tissue are paired with surface weighted average concentrations in waterway BAZ sediment, there is a clear pattern of increasing tissue COPC concentration as sediment COPC concentrations increase (Graphic 32). This relationship is apparent for each COPC in fiddler crab, mummichog, and white perch (whole body)[221], though the relationship for white perch is not as strong as that for the other species. While there is significant variability around the median values, these relationships indicate the importance of the waterway sediment bed as the ultimate source of the COPCs in the aquatic food web. On a smaller spatial scale, the strongest link with waterway sediment was found for fiddler crab, a species that lives in and forages directly on the waterway sediment surface[222] compared to mummichog and white perch that do not feed directly on waterway sediment and that forage across larger areas.

[221] Refer to Figures 4-2 through 4-4 of Appendix I.
[222] Refer to Section 4.1 of Appendix I.



Graphic 32. Relationship between COPC Levels in Waterway Surface Sediment and Mummichog Tissue (Whole Body)

Though there is a strong link with waterway sediment, COPC uptake in waterway biota appears to be mediated through a detritus-based food web rather than direct exposures to waterway sediment. The stable isotope data collected in the waterways indicate that the BCSA food web is detritus based with *Phragmites* detritus from the surrounding marshes the most important contributor.[223] This pattern was found for all primary aquatic consumers studied, including mummichog, white perch, and fiddler crab and other crustaceans. Benthic infauna (e.g., annelids, polychaetes) living within the waterway sediment matrix do not appear to be important dietary components to the BCSA aquatic food web and instead represent a separate biotic compartment not linked to the key consumers in the BCSA waterways.[224] Gut content data indicate that shrimp, amphipods, and other crustaceans are important diet items for BCSA mummichog and white perch.

Analysis of COPC levels in fish and multiple biotic and abiotic compartments indicate that diet and surface water particulate matter are important factors in COPC uptake.[225] As discussed earlier (Section 4.8.3), surface water particulate organic matter consists predominantly of detritus composed of plant material and associated fungi and bacteria. These materials can fuel the base of the BCSA food web. Shrimp, mud crab and other organisms feeding on detritus provide the dietary link between detritus and fish and other consumers.

[223] Refer to Attachment I5 of Appendix I.
[224] Refer to Attachment I5 of Appendix I.
[225] Refer to Section 4 and Attachment I6 of Appendix I.

The link between the BCSA food web and COPCs in waterway sediment is, thus, indirect. Movement of detritus from the marshes into the waterway provides a large proportion of the organic matter comprising the fluff layer on the surface of waterway sediment surface. It is the interaction between the fluff layer and the waterway sediment bed that leads to COPC accumulation in detritus that then enters the base of the BCSA food web. Low COPC concentrations in detritus/fluff and the topmost layer of waterway surface sediment (compared to deeper sediments) limits COPC residues available for uptake.

The findings for the BCSA are consistent with the literature on mercury/methyl mercury and PCB uptake indicating the importance of dietary exposure (e.g., Dutton and Fisher 2014; Rubinstein 1984) and also the importance of particulate matter to the overall uptake. For example, Chen et al. (2014) found that water column particulate methyl mercury was important for explaining between 60 and 90 percent of the variability of body burden in mummichog examined in several East Coast estuaries (including Berry's Creek). These authors also reported a positive relationship between total mercury in sediment and water column particulate, and suggested the resuspension of surface sediment may have contributed to water column particulates. This is the process that has been well documented for the BCSA (Section 6.2.3.2). For PCBs, Stapleton et al. (2001) reported that suspended particulate matter was the main source of exposure for fishes to PCBs in Lake Michigan. Rashleigh et al. (2009) reported that the dominant pathway for PCB accumulation in fish was from detritus to daphnia to fish, consistent with the findings for the BCSA.

Once COPCs enter the food web, the flat trophic structure of the BCSA limits COPC biomagnification. The stable isotope data indicate that the BCSA aquatic food web is compressed, with few (~1) trophic steps between primary producers and fish consumers.[226] Overall, the differences in COPC concentrations across taxa indicate that some biomagnification is occurring, especially for PCBs compared to methyl mercury where the magnitude of difference in concentration across taxa is the greatest.

Methyl mercury and PCB residue levels in white perch are higher than mummichog and other taxa, suggesting that they are the top aquatic predator of the species studied. For methyl mercury, median concentrations in white perch are approximately 2 times higher than those in mummichog in all reaches except LBC and reference sites, where the median concentration is an order of magnitude higher in white perch (Table 6-2). For PBCs, tissue concentrations are in the range of 5 times higher in white perch compared to mummichog, and nearly 100 times higher or more than found in shrimp (Table 6-3).

[226] Refer to Attachment I5 of Appendix I.

Table 6-2. Median Methyl Mercury Concentrations for Waterway Receptors in the BCSA and Reference Areas

Reach	Concentration (mg/kg wet weight)				
	Fiddler Crab	Shrimp	Mud Crab	Mummichog	White perch
UBC	0.080	0.14	0.15	0.16	0.35
MBC	0.061	0.21	0.15	0.16	0.31
BCC	0.039	0.083	0.11	0.14	0.22
LBC	0.040	0.046	0.074	0.08	0.22
Reference	0.027	0.043	0.063	0.079	0.19

Note: Receptors are listed from lowest median COPC concentrations to highest, moving left to right across the table for each COPC.

Table 6-3. Median PCB Concentrations for Waterway Receptors in the BCSA and Reference Areas

Reach	Concentration (mg/kg fresh weight)				
	Shrimp	Mud Crab	Fiddler Crab	Mummichog	White perch
UBC	0.052	0.38	1.28	1.1	5.1
MBC	0.039	0.23	0.53	0.81	5.2
BCC	0.028	0.19	0.26	0.47	2.6
LBC	0.012	0.13	0.18	0.33	2.1
Reference	0.027	0.24	0.24	0.37	1.5

Note: Receptors are listed from lowest median COPC concentrations to highest, moving left to right across the table for each COPC.

This magnitude of difference in COPC residues between white perch and mummichog are not consistent with the findings of the BCSA food web studies. The stable isotope data indicate that white perch and mummichog occupy the same trophic level within the BCSA, a finding consistent with that previously reported for white perch in the Hackensack Meadowlands (Weis 2005). Gut content data also were similar across both species though white perch had a higher proportion of fish in the gut.[227] Because gut content data represent only a snapshot in time (i.e., what was eaten hours before), whereas stable isotopes integrate dietary exposures over weeks to months, stable isotope data maybe a better indicator of trophic position in the BCSA. Nevertheless, while the isotope data provides an integrated measure of trophic position, the differences in instantaneous gut contents indicate that the two species consume dietary items from different trophic positions, which would in turn affect the amount of COPCs derived from dietary uptake. Differences in

[227] Refer to Attachment I5 of Appendix I.

COPC concentration in perch compared to mummichog also could be due to species-specific absorption and metabolism of the COPCs. In addition, white perch migrate seasonally throughout the Meadowlands region (Hardy 1978) and white perch sampled in the BCSA are generally between 2 to 3 years of age[228], it is likely that some exposure outside of the BCSA has occurred. This is in contrast to mummichog, which have a smaller spatial range, spending their life within BCSA (Lotrich 1975). The levels of COPCs in white perch collected from reference sites support that conclusion.

In summary, these collective results indicate that COPC concentrations in biota are linked to sediment COPC via the detrital-based food web.

6.3.2 Marshes

COPC uptake in the *Phragmites* marshes is limited primarily to the detrital layer and the top few centimeters of sediment below the detrital layer, where the biological activity in concentrated.[229] Marsh invertebrates and other organisms feeding on or in the detrital layer on the marsh surface can be exposed, and COPCs have been detected in marsh invertebrates.

Accumulation of COPCs present at depth in the marsh sediments is limited. Some COPCs accumulate in *Phragmites* roots, but the data indicate that little of this COPC mass is translocated to the above-ground biomass and, in turn, in the detritus layer that covers nearly 100 percent of the marsh surface.[230] Particulates transported from the waterway and deposited in the marsh are the likely source of COPCs present in marsh detritus.

6.4 <u>Receptors and Pathways</u>

People potentially can be exposed to COPCs via direct contact with sediment or surface water, inhalation, or ingestion of biota that has accumulated COPCs. Recreational users of the waterway are the primary human receptor group for the BCSA. Fishing, crabbing, and kayaking/canoeing are current and plausible future primary recreational activities. Observations during the RI by field crews and the camera survey indicated that most of the human activity is focused in and around waterway areas that are accessible via upland features (e.g., bridges) that allow users to avoid the dense marsh vegetation and soft waterway sediments to reach the waterway. Boat access to BCC from the Hackensack River also has been observed, with boat traffic limited to the lower reach near the confluence with the river.

Wide fringing ditches and dense stands of *Phragmites* are barriers to human use of the marshes. Some contact with marsh sediments by recreational users can occur adjacent to waterway access

[228] Refer to Section 3 of Appendix I.
[229] Refer to Section 3.1 of Appendix I.
[230] Refer to Section 3.1 of Appendix I.

points, but otherwise, recreational exposure in the marshes is highly unlikely and has not been observed. In the future, workers could access marsh sediments if a construction project around or through the marshes is initiated, though the nature of the construction would likely be of shorter duration compared to recreational exposures.

There is no residential exposure pathway that is complete within the BCSA waterways and marshes. Residential land use in the BCSA watershed is concentrated in the upland area, outside of the 100-year flood zone. Recent residential housing approvals closer to the tidal areas have been built, or are approved, in a manner that prevents residential exposure. These residences do not have an existing or planned direct recreational connection to the tidal waterways and marshes. Thus, any people living in close proximity to the BCSA waterways and marshes would have an exposure scenario that is covered by the recreational scenarios. Commercial and industrial land use is concentrated around the tidal area. Local worker exposures could mimic those of recreational users.

A variety of ecological receptors can potentially be exposed to COPCs in both waterway and marsh environments. Receptors near the top of the BCSA food web are at greatest potential risk from exposure to biomagnifying compounds such as methyl mercury and PCBs via the diet, but all organisms can be potentially exposed via direct contact with contaminated media (sediment and surface water).

Key ecological receptors in the BCSA waterway and marsh (Figure 2-1) habitats that are important to defining potential for risk are:

Waterway

- Piscivorous bird: Great blue heron—a fish-eating wading bird
- Piscivorous and insectivorous bird: Black-crowned night heron—a fish- and invertebrate-eating wading bird
- Invertivorous bird: Spotted sandpiper—a shorebird that eats invertebrates on the BCSA mudflats
- Piscivorous and invertivorous mammal: Raccoon—a fish- and invertebrate-eating mammal
- Benthic macroinvertebrates—the invertebrate community inhabiting the mudflat and subtidal zone of the waterways
- Mummichog and white perch—the dominant fish of the BCSA fish community.

Marsh

- Marsh wren and red-winged black bird—invertebrate-eating song birds that inhabit the *Phragmites* marshes
- American woodcock—an earthworm-eating bird that could inhabit the drier and more scrub shrub habitats of the UPIC area
- Muskrat—an aquatic mammal that consumes *Phragmites* roots
- *Phragmites* marsh community—the primary producer and key energy component fueling the BCSA food web.

6.5 Natural Recovery

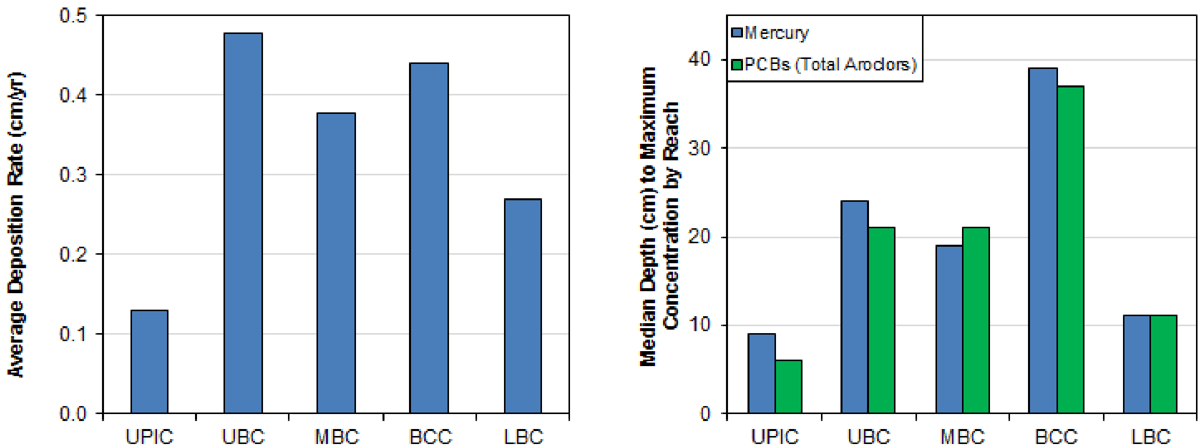
Consistent with being an emergent marsh system, the BCSA is net depositional and accumulates sediment derived from tidal exchange with and storm surges from the Hackensack River estuary, uplands baseflow and runoff, and autochthonous production.[231] Emergent marshes typically act as a sink for sediment—filling in with sediment over time, especially during periods of sustained sea level rise. Profiles of COPCs in site sediment cores confirm that cleaner sediment is accumulating throughout a majority of the BCSA waterways and marshes, resulting in burial of higher concentration materials that reflect historical maximums (Graphic 14). This pattern of recovery occurs across much of the system and is consistent with other lines of evidence (e.g., deposition rates based on profiles of geochronological markers and SET data, sediment flux and trapping estimates, and sediment transport modeling)[232], which collectively show that the BCSA is accumulating sediment over time and that more recently deposited shallow sediment generally contains far lower concentrations of COPCs than historically deposited, deeper sediment. Further, although COPC concentrations remain elevated in UBC and MBC surface sediments relative to the reference sites, the concentrations in BCC and LBC surface sediment are approaching the reference site concentrations.

6.5.1 Marshes

With few exceptions, peak mercury and PCB concentrations are observed at depth in marsh sediment cores, and vertical profiles of these COPCs are similar across cores within a given marsh (Section 5.2). Deposition rates in the BCSA tidal zone marshes range from approximately 0.16 to 0.6 cm/yr (average = 0.40 cm/yr; Graphic 33).[233] Mercury and PCB subsurface maxima typically occur at depths of 15 to 25 cm in UBC and MBC marsh sediment (Graphic 33); most often at a

[231] Refer to Section 3.1 of Appendix G.
[232] Refer to Appendices F and G.
[233] Refer to Figure 3-10 of Appendix F.

similar depth as peak ^{137}Cs concentration—suggesting that peak mercury and PCB loading to the BCSA occurred in the 1960s. In the BCC marshes, the subsurface maximum depths are somewhat deeper than in the upper reaches (26 cm for mercury and 40 cm for PCBs). Lower sediment deposition rates were measured in LBC marsh cores, and these cores show comparatively shallower average subsurface maxima depths (12 cm for mercury and 9 cm for PCBs).



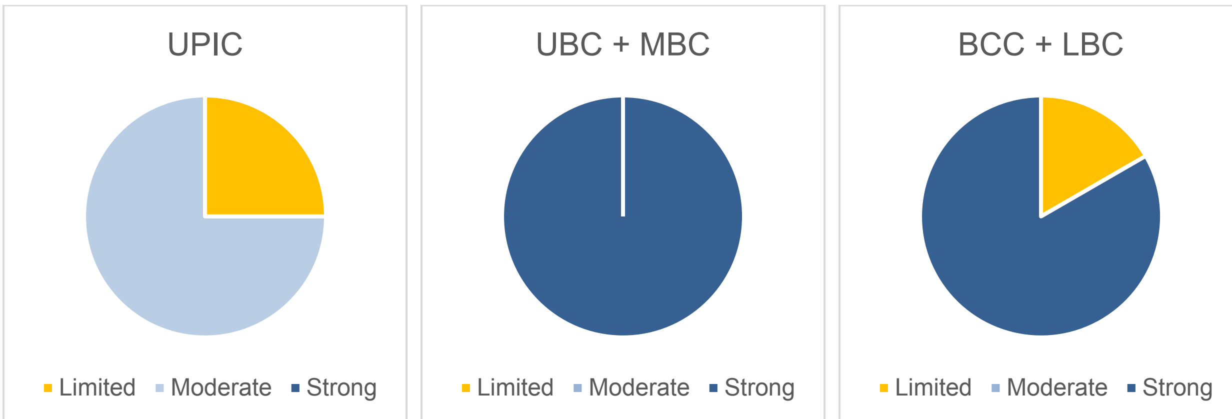
Graphic 33. Average Sediment Deposition Rates and Depth of Peak Mercury and PCB Concentration in Marsh Sediment[234]

The subsurface mercury and PCB peaks indicate that ongoing accumulation of less contaminated sediment over time is resulting in natural recovery in the tidal zone marshes. A greater overall degree of reduction in mercury and PCB concentrations from subsurface maxima is observed in marsh surface sediment from UBC and MBC where a greater density of historical industrial and municipal sources were located and peak historical concentrations at depth in sediment are highest. The reduction between the subsurface maxima and the sediment surface is also evident in BCC and LBC; however, the overall mercury and PCB concentrations in these areas are relatively low throughout the sediment column compared with UBC and MBC so the difference is less pronounced. COPC concentrations in the lower reaches are generally similar to the concentrations measured in reference site marsh sediment (Section 5.1).[235]

Exceptions to the observations of broad natural recovery in the marshes are few (Graphic 34). The most notable exception is in UPIC marsh, where peak mercury and PCB concentrations were observed within the top 10 cm of sediment in a majority of the marsh cores, with a median depths of peak concentration of approximately 6 to 9 cm. This appears related to the installation of the PIC tide gate in 1967 which prevents tidal flow into UPIC and cuts off the associated supply of sediment. The limited sediment supply to UPIC is reflected by the lower deposition rates measured

[234] Deposition rates based on the analysis of geochronological data presented in Section 3.2.2 and Attachment F1 of Appendix F.
[235] Refer to Section 3.4 of Appendix F.

in UPIC marsh (0.06 to 0.22 cm/year) compared to the rates measured in BCSA tidal zone marshes. Despite the lower rate of sediment deposition, the COPC profiles in UPIC marshes indicate that natural recovery is occurring and concentrations of mercury and PCBs in the top 0–2 cm of sediment are typically less than the peak concentrations at depth.

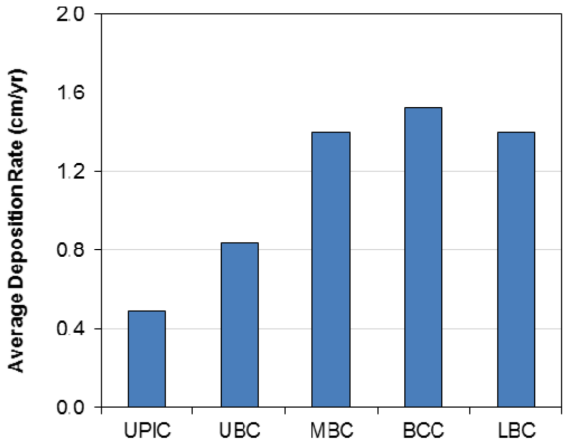


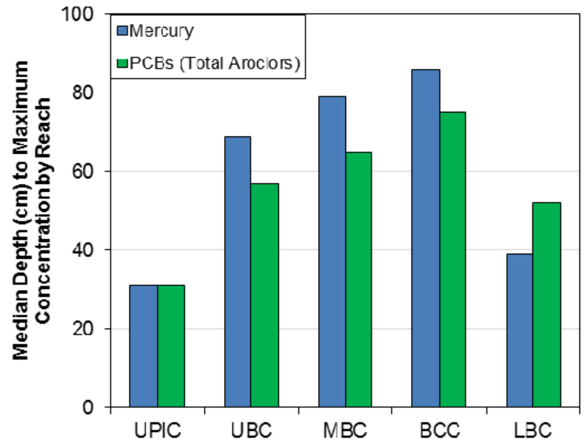
Graphic 34. Summary of Marsh Sediment High-Resolution Cores Exhibiting Strong, Moderate, and Limited Evidence of Natural Recovery.[236]

6.5.2 Waterways

Sediment deposition rates estimated from high-resolution cores in the BCSA waterways typically range from 0.75 to 2.0 cm/yr (Graphic 35).[237] Overall, these deposition rates are more than double the rates estimated for the marshes.[238] Consistent with higher deposition rates, the waterway subsurface maxima in high-resolution cores are deeper (medians range from 39 to 86 cm) than the marsh subsurface peaks across all BCSA tidal zone reaches (Graphic 35). Mercury and PCB subsurface maxima, averaged by reach, occur from 57 to 79 cm deep in UBC and MBC and from 39 to 86 cm deep in the BCC and LBC.

[236] Refer to Attachment F1 of Appendix F.
[237] Refer to Attachment F1 of Appendix F.
[238] These rates are based on ^{137}Cs profiles and represent average rate of deposition over the past approximately 50 years. It is possible that higher deposition rates occurred in the waterways during the late 1960s and 1970s due to tidal prism reductions resulting from marsh filling and that present-day deposition rates in the waterways are somewhat lower. Further, the rates of deposition in the marshes approach those in the waterways when evaluated on a mass basis, as the marshes are more than double the area of the waterways.





Graphic 35. Average Sediment Deposition Rates and Depth of Peak Mercury and PCB Concentration in Waterway Sediment[239]

Natural recovery is also evident in the majority of cores of high-resolution waterway sediment, with 24 of 26 cores exhibiting evidence of recovery from historical maxima mercury and PCB concentrations (Graphic 35).[240] Mercury and PCB concentration vertical profiles in waterway cores exhibit more small-scale fluctuations with depth than is observed in the marsh cores. This is the expected pattern, as the BCSA main channel and several tributaries are subject to episodic disturbance unlike the marshes. However, despite these influences, the COPC profiles show a long-term trajectory of net sediment accumulation and natural recovery throughout the majority of the BCSA waterways.

A majority of the tidal zone waterway cores showing limited recovery are located in UBC and MBC, with only two total cores showing limited recovery in LBC and BCC (Graphic 36). These patterns are consistent with the proximity of UBC and MBC to a greater density of historical contaminant sources to the BCSA (Section 6.1) and the greater influence of episodic storm events on UBC than in the lower reaches (Sections 4.7.2 and 5.2.1). Sediment mercury and PCB concentrations in BCC and LBC are lower throughout the vertical profile of the cores than in UBC and MBC.[241] Similar to the BCC and LBC marshes, trends in decreasing concentrations from the subsurface to the surface are frequently more subtle in BCC/LBC waterway sediment compared to UBC and MBC waterway sediment.

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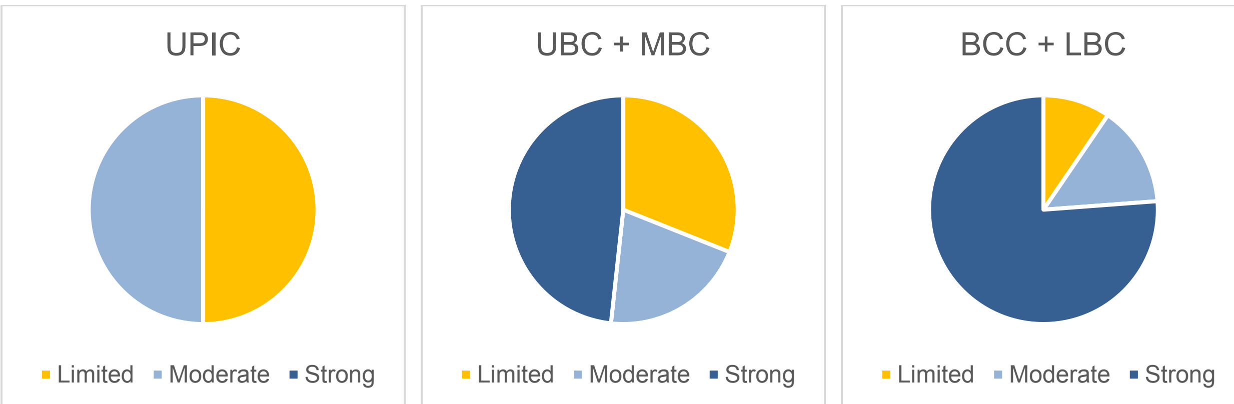
[239] Deposition rates based on the analysis of geochronological data presented in Section 3.2.1.3 and Attachment F1 of Appendix F. The single high-resolution core was collected in UPIC and exhibited a weak ^{137}Cs peak. To be consistent with the approach taken with other cores collected at the site, a deposition rate of 0.5 cm/yr was calculated based on the ^{137}Cs data; however, this rate estimate is uncertain due to the weak ^{137}Cs peak. Estimates based on ^{210}Pb data from this core suggest a deposition rate on the order of 1 cm/yr.
[240] Refer to Table 2b of Attachment F1, Appendix F.
[241] Refer to Section 3.3.3 of Appendix F.

As is seen with UPIC marsh, a lesser degree of natural recovery is apparent in UPIC tributary sediment compared to the tidal zone waterways of the BCSA (Graphic 36). Peak mercury and PCB concentrations occur at a median depth of 31 cm in high-resolution cores of UPIC tributary sediment, with generally lower concentrations at the surface of the sediment bed. These data suggest some natural recovery has occurred in UPIC tributary, but at a slower rate than in the BCSA tidal zone. Further, other lines of evidence (e.g., low ^{137}Cs activity, highly variable COPC profile) suggest that natural recovery in the tributary is not strong.



Graphic 36. Summary of Waterway Sediment High-Resolution Cores Exhibiting Strong, Moderate, and Limited Evidence of Natural Recovery. [242]

6.5.3 Fish

Historical data on COPC residues in fish tissue are limited and changes in analytical methods render historical data of marginal use. Tissue data have been collected from the BCSA and reference areas throughout the period of 2009 to 2015, and overall, COPC concentrations are variable across years and no temporal trend in tissue concentrations is apparent.[243] Temporal variability is more pronounced in the upper reaches of the system (UBC, MBC) in comparison to the lower reaches (BCC, LBC) and greatest for methyl mercury compared to mercury and PCBs. Continued monitoring will support additional analysis regarding temporal patterns and recovery.

6.5.4 Summary

Overall, the RI data set and associated analyses and modeling indicate that natural recovery of BCSA sediment is occurring at varying degrees throughout a majority of the BCSA, with the degree of recovery depending on geomorphic position and location in the system. Surface sediment COPC concentrations in the southern portion of MBC, BCC and, in particular, LBC are approaching the concentrations measured in reference area sediments, consistent with the daily

[242] Refer to Attachment F1 of Appendix F.
[243] Refer to Attachment I4 of Appendix I.

exchange of these reaches with the Hackensack River estuary and the ongoing deposition of estuarine sediment within the BCSA. Surface sediment concentrations in UBC and much of MBC remain elevated compared to regional conditions despite clear evidence of long-term deposition and strong natural recovery from historical maxima in these areas. These observations reflect the fact that historical concentrations in these areas are substantially greater than in the lower reaches and that these reaches are less frequently exchanged with the Hackensack River than the lower reaches.

Compared to the marshes, the waterways are subject to a greater degree of mixing and redistribution due to interaction of fluff layer particulates with the surface of the sediment bed and episodic resuspension during infrequent, large magnitude storm events. Semi-diurnal tidal flooding results in the net transport of COPCs derived from adjacent waterways to the BCSA marshes—a process that slows the natural recovery of the marshes to regional levels. Similarly, particulate resuspension also results in the redistribution of COPCs from higher concentration areas of the waterways to lower concentration areas of the waterways, and likely slows recovery of sediment in the lower system to regional levels. Other sources of COPCs, such as the Hackensack River, also contribute to the COPC concentrations in BCSA abiotic and biotic media.

SECTION 7

HUMAN HEALTH AND ECOLOGICAL RISK

As agreed with EPA, the baseline ecological and human health risk assessments will be submitted after the draft RI Report. The final RI Report will include the final risk assessment appendices and an overall summary in this section of the main text.

SECTION 8

SITE-SPECIFIC STUDY QUESTIONS

A set of site-specific study questions was developed in the RI/FS Work Plan to direct and focus the strategic design of the field studies and subsequent analyses. The study questions were framed to address the important elements of the CSMs and to ensure that the data collected would meet risk assessment and remedy development needs. These questions and the corresponding study objectives are consistent with the relevant EPA guidance cited throughout the Work Plan and subsequent Work Plan Addenda.[244]

The study questions were identified and discussed in detail in the RI/FS Work Plan and that discussion was updated in the Phase 1 Report (BCSA Group 2010) and Phase 2 Report (BCSA Group 2012a). This updated discussion of the 12 site-specific questions is presented in relation to the combined three phases of the RI and in consideration of the analysis and key findings presented throughout this RI Report. Study questions 1 through 7 are presented in Section 8.1 and relate to the physical, chemical, and biological characteristics of the site that define site-related risks to human health and ecology. Study questions 8 through 12, presented in Section 8.2, relate to the evaluation of remedial alternatives at the site. Although the findings of the RI and risk assessments presented in this RI Report provide the foundation for remedy evaluation and are discussed here, study questions 8 through 12 will be a focus of discussion in the FS.

8.1 Study Questions Related to Chemical, Physical, and Biological Processes that Define Site-Related Risks

The following presents a discussion of the study questions that relate to the distribution of stressors in relation to human and ecological receptors, important hydrodynamic and sediment transport processes that influence the distribution of stressors within the BCSA, and risks posed by stressors in the BCSA.

8.1.1 Study Question 1 (Stressors): What are the major stressors (physical, chemical, and biological) and how are they distributed in relation to the receptors important to defining risk?

The distribution of the major stressors is well understood as a result of comprehensive data collection over 7 years (2009 through 2015), including investigations across a wide range of site conditions. Characterization in the RI is focused on understanding the risks posed by site-related chemical stressors, especially at potential exposure points (e.g., contact with surface water and the top few centimeters of sediment). The primary COPCs include mercury, methyl mercury, and total

[244] Refer to Appendix C.

PCBs. In addition, samples for the complete TAL and target compound list chemicals have been collected throughout the BCSA and have been evaluated in detail as part of the baseline risk assessments.

The following findings related to COPC distribution in all media are based on interpretation of the full RI data set:

- COPCs are more elevated in concentration in the upper portion of the system, with highest concentrations typically in UBC and UPIC, and demonstrate a declining trend to lower concentrations in the lower reaches (LBC/BCC) as result of several factors including:

  - Proximity to many of the historical sources of COPCs

  - Hydrology and sediment dynamics that favor retention of COPCs in the upper reaches of the system

  - A high frequency (twice a day) of nearly complete tidal exchange of surface water and associated suspended particles in the lower reaches with the Hackensack River estuary.

- COPCs are higher in concentration in the waterway surface sediment than in the surface sediment of the adjacent marshes, except for methyl mercury, which is higher in marshes.

- In the waterways, COPC concentrations are typically at a higher concentration at depth than in the BAZ where potential ecological exposure is greatest, with a few exceptions. Most notably, peak methyl mercury occurs in the top 2 cm of waterway sediment as a result of biogeochemical processes.

- COPCs in fine particulates resuspended from the thin mobile fluff layer on the surface of the waterway sediment bed are the primary source of COPCs to the aquatic food web and the primary ongoing source of COPCs depositing to the marsh surface. Waterway sediment below the surface fluff layer and deeper BAZ, where exposure is minimal, is typically more elevated in COPC concentration than the BAZ, and is stable throughout the majority of the waterways. The exceptions to this are few and are isolated to areas of the waterway, such as meander bends and entry points for upland storm runoff, that are subject to higher velocity conditions during rare but major storm events (e.g., Hurricane Irene).

- In marsh sediment, the highest COPCs concentrations are found in the subsurface and are therefore physically isolated from direct exposure points. The exception is UPIC Marsh, where the highest COPC concentrations occur within the top 10 cm of sediment at many locations.

- COPCs are only minimally transferred to above-ground marsh vegetation through biouptake. As a result, the *Phragmites* detritus that forms a thick layer on top of the marsh surface sediment, and that is exported to the waterways, is also low in COPC concentrations.

- COPCs in biota show a consistent trend of decreasing concentrations from the upper reaches to the lower reaches. This pattern in seen in all biota except blue crab, and parallels the COPC trends in waterway and marsh sediment.[245] When tracked across the BCSA reaches, changes in COPC concentrations in waterway biota clearly parallel those in sediment and surface water.

- COPCs exhibit low concentrations in marsh invertebrates, resulting in generally lower exposure and lower risks in the marshes compared to waterways.

- COPC are elevated in mudflat sediment in UBC and MBC where some ecological receptors forage. Shorebirds in particular receive most of their exposure on mudflats where they probe and skim the sediment for prey. Calculated exposures are highest in the mudflats of the upper reaches of the system compared to the lower reaches. Recreational and other human uses of mudflats and the remainder of the waterway are limited, given the barrier posed by narrow fringing ditches and/or dense *Phragmites* marshes.

- Mercury concentrations in ambient air are generally low across the site, and are not a significant source of human or ecological receptor exposure.

A number of other stressors exist in the BCSA. Dissolved oxygen depression, nutrient loading, and ammonia concentrations in sediment, in combination with strongly shifting salinity gradients across the BCSA, were concurrently evaluated with COPC data to determine how site-related COPCs and other stressors are interrelated and jointly influence the habitat qualities, aquatic community composition, and ecosystem dynamics.

8.1.2 Study Question 2 (Stressors): What are the stressor sources (current and historical) in relation to the receptors important to defining risk?

The sources of stressors in relation to the receptors are well understood. Numerous historical industrial and sewage discharges contributed significantly to COPCs found in the BCSA, including mercury, PCBs, TAL metals, and other compounds. The higher concentrations of COPCs are almost always found buried under cleaner sediment (greater than 30 cm in most areas of the waterways and greater than 20 cm in most areas of the marshes) that has deposited in the BCSA over the last approximate 50 years. Modeling and bathymetric measurement[246] indicate that these buried COPCs are likely to remain buried—with only a small fraction of the waterways subject to

[245] Refer to Appendix I, Figure 4-1

[246] Refer to Section 3 of Appendix G.

erosion during rare higher-energy storm events (e.g., hurricanes). There is confidence in these findings, given that the data set upon which they were based included the consequences of three major and historic storm events that occurred during the RI (Hurricane Irene in 2011—a once in 100 year event; Topical Storm Lee in 2011; and Hurricane Sandy in 2012—a once in 500 year tidal surge event). As a consequence, these buried COPCs have limited or no potential to be a source of COPCs for direct ecological and human exposure.

There remains a variety of current sources of stressors that contribute to bioavailable COPCs in the BCSA. The RI has adequately characterized these sources to support the development of effective remedies that will reduce unacceptable risks. The extent and magnitude of current sources were investigated throughout the RI and include the following:

- Secondary sediment sources include surface sediment in waterways containing COPC concentrations that are elevated compared to the regional condition. Routine particulate resuspension of the waterway surface fluff layer (top 0.5 cm of sediment) can transport COPCs that have sorbed to fluff layer particulates from the underlying sediment. Large (once every 3 years) storm events capable of resuspending up to the top 3 cm of bedded sediment in localized areas of the waterways[247] result in COPC transport from the surface of the sediment bed to surface water, and redistribution within the waterways and marshes. Rare, major storm events, such as Hurricane Irene, can lead to redistribution of deeper sediments from localized areas of the waterways. Secondary sources contribute to a reduction of the natural recovery of sediment in the marshes and the downstream reaches of the waterways. Receptors throughout the BCSA are exposed to COPCs from these secondary sediment sources. The secondary sediment sources are limited to waterways (including some tributaries) primarily in UBC and MBC.

- Upland runoff contributes approximately 30 percent of the inorganic sediment that deposits in the BCSA. Although surface water and sediment data collected during the RI suggest that runoff does not represent a substantial ongoing source of COPCs to the BCSA tidal zone, the potential influences of upland runoff will need to be considered during the FS, as well as the influences of non-permitted sewage discharges that are periodically evident in upland drainages (e.g., East Riser tide gate).

- Outfalls from ongoing discharges to Berry's Creek and its tributaries (approximately 18 permitted and 26 unpermitted) have been documented. Sampling results and visual observations indicate continuing contributions of CERCLA (e.g., PAHs) and other stressors (i.e., dissolved oxygen below 5 ppm for extended periods) from some sources.

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[247] Based on sediment transport modeling of a range of storm rainfall magnitudes and profiles of COPC and geochronological marker in high resolution cores (Section 3.5 of Appendix G).

- Atmospheric deposition of mercury and PCBs contributes to the concentrations of the COPCs in surface sediments, surface water, and marsh vegetation (exposure points), as well as fish tissue. COPCs deposited through atmospheric deposition likely do not contribute substantially to overall concentrations in the BCSA relative to legacy sources, but their relative bioavailability in comparison to historical sources and their long-term contribution to post-remedy COPC concentrations may be important.

- Groundwater is not a known or suspected source of CERCLA hazardous substances into the tidal portion of the BCSA. The thick, low permeability clay underlying the BCSA greatly minimizes the potential for regional or sub-regional discharges of groundwater and related stressors to the tidal zone of the BCSA. Within the tidal zone, there are two areas of saturated media flow that were evaluated but not found to be significant contributors to surface water or sediment contamination: interflow from marshes to waterways, and tidal exchange with landfills that are being closed in LBC under NJDEP oversight.

- Hackensack River is an important source of the historical and current loading of several regional stressors (e.g., dioxins, furans, ammonia, biological oxygen demand, and fecal coliform). Sediment flux analysis indicates the Hackensack River contributes more than 70 percent of the inorganic sediment that is deposited in the BCSA on an ongoing basis (proportionately more in LBC and BCC than in UBC and MBC). In addition, surface water monitoring data indicate stressors from POTW and CSO discharges to the Hackensack River (e.g., biological oxygen demand, ammonia, fecal coliform, nutrients) move into the BCSA with incoming tides. Receptors throughout the BCSA are exposed to stressors originating in the Hackensack River. Elevated levels of PCBs and mercury in biota from the Hackensack River and the broader Meadowlands region underscore the presence of regional sources of COPCs.

All of these sources contribute stressors to the BCSA waterway and marsh habitats. Though secondary sediment sources are the primary ongoing source of the primary COPCs, these other sources also contribute chemical and nonchemical stressors that can influence receptors within the BCSA. As a result, these sources will be a continuing part of the fate and transport analysis, baseline risk assessment, and risk analysis in the alternatives evaluation.

8.1.3 Study Question 3 (Receptors): What are the key human and ecological receptors important to defining risk and how are they distributed throughout the BCSA?

The primary human receptor group under current conditions is recreational users.[248] Human recreational use of the BCSA will be a continuing future use. As part of the RI field efforts, observations (direct and with onsite cameras) of human use were compiled and analyzed.

[248] This use is consistent with short- and long-term management plans for the area as developed by the NJMC and now administered by the NJSEA.

Information collected included the type and location of activity. These data document that most human activity is limited to a few locations where persons can obtain access to Berry's Creek via the upland (i.e., bridges), avoiding the dense marsh vegetation and soft waterway sediments.

Human activities include some crabbing and fishing, including bait fishing of the small white perch and mummichog that predominate in the BCSA fish community. Updated signage approved by NJDEP on the regional Newark Bay Complex crabbing and fishing prohibitions was posted throughout the BCSA in 2011, and is checked and replaced annually as needed. Residential land use in the BCSA watershed is concentrated primarily in the uplands area, outside of the 100-year flood zone. Commercial and industrial land use is concentrated around the tidal zone, with a relatively small number of residential buildings near the tidal areas. These residences do not have a direct recreational connection to the tidal waterways and marshes. Other recreational activities include boating in the lower portion of the system, mainly in BCC.

Biota community surveys (e.g., flora and vegetation, marsh and waterway invertebrates, fish, wildlife) were conducted throughout the RI to provide, in part, information for identification of potential ecological receptors in the BCSA. In addition, functions and values analysis of the marshes was completed. These studies indicate how the key ecological receptors are distributed:

- Marsh vegetation is generally similar across the BCSA, as it is throughout the Hackensack River estuary, and is typical of estuarine marshes that predominate in the Meadowlands region. *Phragmites* is the ecologically dominant species; it became established in response to past physical disturbances and related increases in salinity from fresh water to brackish. Other species occur throughout the disturbed areas, along edge areas, and in higher salinity areas in the lower reaches of the BCSA.

- Marsh invertebrate communities are similar throughout, with any differences likely due to the influence of increasing salinity from north to south. The marsh macroinvertebrate community is dominated by a few taxa distributed primarily in the detrital layer and above-ground vegetation, with a composition and diversity similar to or better than that in reference site marshes.

- In the waterways, mummichog, white perch, and invertebrates (e.g., annelids, fiddler crabs, blue crabs and a variety of crustaceans) are the key aquatic receptors. These species are distributed throughout the BCSA waterways. Of these, white perch and blue crab migrate seasonally in the broader region and spend only a portion of the year in the BCSA. Wading birds are also key ecological receptors that forage along mudflats and in shallow water. Shorebirds forage on mudflats throughout the BCSA, with UBC and LBC providing the greatest amount of appropriate habitat.

Ecological receptors for the risk assessment were selected based on consideration of habitat factors (type, quality, and receptor distribution), but also based on susceptibility and sensitivity to COPC exposures and on consideration of the utility of receptor-specific evaluations to support risk management decisions to address COPCs.

8.1.4 Study Question 4 (Hydrodynamics and Sediment Dynamics): How do water and sediments move into, out of, and within the tidal portion of the BCSA, and what are the spatial and temporal patterns throughout the BCSA?

Understanding water and sediment movement is the basis for understanding COPC fate and transport in the BCSA. The extensive RI work has confirmed that the flow regime is a vertically well-mixed (i.e., non-stratified), tidally dominated system. Freshwater inputs (surface water and groundwater) comprise a small percentage (<1 percent) of the overall flow, except during large precipitation events when the volume of fresh water can increase significantly. Tidal flows in the BCSA are small relative to the tidal flows in the larger Hackensack River estuary, which are estimated to be approximately 10 to 20 times greater than in the BCSA. Tidal flows result in a high degree of exchange between the lower reaches (LBC and BCC) and the Hackensack River, resulting in residence times on the order of a day. MBC and UBC are more distant from the river, and the lesser exchange of these reaches with the river results in residence times of 3 to 6 days. Under typical dry weather conditions, little to no water in UBC reaches the river on a single ebb tide before the tide reverses and pushes the water back up the system.

Overall, the system is a net depositional estuarine environment, and the physical data reflecting the historical record indicates it will remain so in the absence of substantial (i.e., regional-scale) system modifications. Approximately 65 percent of the watershed lies within the 100-year flood zone, indicating the watershed has an overall low gradient that does not produce peak flows capable of moving significant sediment mass. Sediments accumulated in the BCSA are derived from estuarine, upland, and autochthonous sources. Rates of accumulation vary spatially and temporally depending on geographic location, morphology, and relative sea level rise. However, some areas of limited extent are not accumulating sediment or are accumulating sediment at a much lower rate. For example, UPIC above the PIC tide gate appears to have lower rates of sediment deposition. This is due to relatively low sediment inputs from the surrounding upland sub-watershed, which is a small area that is highly developed with relatively flat slopes, and because the UPIC tide gate, when functioning, prevents the movement of sediment from the tidal zone into UPIC. Other areas with low sediment deposition occur where upland runoff is concentrated, resulting in higher velocities as it enters the tidal portion of the BCSA, such as along the east side of Eight Day Swamp; along portions of the thalweg; in the pools at meander bends in the main channel; near the various tide gates; and near the outfall from the NJSEA complex.

Understanding sediment transport is necessary to understand COPC fate and transport because most COPCs sorb strongly to the particulate phase. Sediment transport, as quantified by mass flux into and out of the BCSA, varies depending on the composition (inorganic versus organic) of the particulates. Sediment enters the BCSA from the Hackensack River estuary on a continuous basis, with the composition of the average incoming tide estimated to be 85 percent inorganic and 15 percent organic. The Hackensack River estuary is the primary source of inorganic particulates to the study area, especially in LBC, BCC, and MBC. Upland areas also contribute inorganic particulates to the BCSA (mainly UBC), mainly during precipitation events. Baseflow is an insignificant source of particulates due to low volume and low suspended solids concentrations.

Organic particulates primarily derived from the marshes comprise a substantial proportion of the suspended particulates pool in the BCSA and exhibit different dynamics than inorganic particulates. The organic particulates are largely derived from plant senescence and decomposition within BCSA marshes. A large mass of organic matter is produced in the BCSA marshes during the growing season, and this organic matter is substantially lower in COPC concentrations (over an order of magnitude) than sediment in the top 5 to 10 cm of the marshes and waterways. Some of this organic matter is deposited directly on the marsh and waterway sediment surface where most of it degrades to fine particulate organic matter and becomes integrated into the sediment with the inorganic particulates. Fine organic particulates derived from marshes along the Hackensack River and particulates from other sources are also delivered to the BCSA with tidal flow. Monitoring during the RI has shown there is a net flux of fine particulates (inorganic and organic) from the waterway into the marshes during high tides. Fine particles are retained in the marsh and contribute to long-term sediment accumulation.

Measurements during the RI indicate net accumulation of sediment has occurred over time, at typical deposition rates of 0.75 to 2.0 cm/year in the waterways and 0.2 to 0.6 cm/year in the marshes. There is episodic reworking and redistribution of the top 3 cm of surface sediment in localized waterway areas during large storm events (e.g., 3 year return frequency). Deeper (e.g., >10 cm) erosion of the sediment in localized waterway areas can potentially occur during rare large storm events (i.e., return frequency of one in 100 years), but only in limited areas of the waterways. The deeper waterway sediments, which generally contain more elevated COPC concentrations, were not affected by the large storm events that occurred during the RI (Hurricane Irene, Tropical Storm Lee, and Hurricane Sandy) across the majority of the BCSA, as is evidenced by COPC and ^{137}Cs profiles in the high-resolution cores, and the bathymetric change analysis. The storms apparently had little to no effect on the marshes, as evidenced by several lines of evidence including 1) the aerial photograph analysis, 2) the detritus layer remaining intact, 3) the clear and consistent pattern of COPCs and ^{137}Cs in the high-resolution cores, 4) the continuous accretion indicated by annual monitoring of SET in the BCSA throughout the RI, and 5) simulations conducted using the validated sediment transport model.

8.1.5 Study Question 5 (Chemical Fate and Transport): What are the key physical, chemical, and biological processes controlling the relationships between each stressor, exposure pathway, and ecological and human receptor exposure?

The relationships between each COPC stressor, exposure pathway, and receptor within the BCSA are controlled by COPC fate and transport processes. Overall, the greatest risks are predicted for receptors using the waterway, and COPC accumulation in fish and other aquatic species is an important pathway for receptor exposure. As is described in Section 6.3, the collective RI results indicate that COPC uptake in waterway biota appears to be mediated through a detritus-based food web, with *Phragmites* detritus from the surrounding marshes supplying the particulate organic matter that fuels the base of the BCSA food web. Shrimp, mud crab, and other organisms feeding on detritus and other POC provide the dietary link between detritus and fish and other consumers. COPCs enter the base of the food web via the interaction of detritus with COPCs in waterway sediment, and movement of the particulate matter into the water column during tidal processes. This particulate matter also moves back into the marshes where it contributes to COPC uptake in the marsh food web.

Detailed evaluation of surface water and surface sediment dynamics using discrete sampling and optically-based instrumentation provided confirmation that the primary COPCs are largely bound to particulates (a large proportion of which are detritus), and fine particulates entering marshes from waterways are strongly retained in marshes. Other data (e.g., the nearly 1:1 relationship between COPC concentrations in surface water and COPC concentrations in the top 2 cm of waterway sediment; Graphic 21) indicate that COPC concentrations at the surface water interface (top 2 cm or less) are the most important factor controlling water column quality. As such, a detailed understanding of the processes that influence contaminant distribution in waterway surface sediment, and transport from these sediments to the water column and to the marshes, is important to support completion of the risk assessment and to support the design of effective remedies that decrease the magnitude of exposure to receptors.

The abundance of organic matter in BCSA sediment and surface water strongly influences the fate and transport of COPCs in the BCSA. The COPCs have a strong affinity for POC and, thus, strongly associate with the particulate phase, both in bedded sediment and in suspended particulates in the water column; therefore, COPC fate and transport is closely tied to that of particulates within the BCSA. As is discussed in detail in Appendices F and G and summarized above, the collection of numerous multi-depth cores of sediment throughout the RI, and other studies such as detailed bathymetry analysis and SET data, provide the empirical basis for demonstrating the stability of COPCs in buried sediment. Isolation through burial by cleaner sediment is a primary factor limiting exposure and uptake of COPCs in biota.

Multiple data sets, such as high temporal resolution monitoring of suspended solids and COPC concentrations in the water column over multiple tidal and climatic conditions, show that particulate deposition and resuspension to/from the fluff layer at the surface of the sediment bed is an important mechanism by which COPCs are transported from waterway surface sediment to the water column. The high organic content of the water column particulates (average of 26 percent) provides considerable capacity to sorb COPCs when the particulates deposit to the fluff layer and are in contact with the surface of the waterway sediment bed. In turn, resuspension of particulates (and associated bound COPCs) from the fluff layer transports COPCs to the water column. Because detritus represents a large proportion of the fluff layer particulates, these processes are the primary mechanism by which COPCs enter the detritus-based food web (Sections 6.3 and 6.4). In addition, deposition of these particulate-bound COPCs on the surface of the marsh is an important factor influencing ecological exposure to and uptake of COPCs in the marshes.

Organic matter also has important influence on BCSA sediment biogeochemistry, which affects the bioavailability and mobility of COPCs through biogeochemical transformation—most notably the formation of mercury sulfides and mercury methylation and demethylation. The influence varies between the waterways and marshes. As a result, COPCs show some variability in bioavailability across the BCSA (e.g., due to differences in organic matter concentration, redox zonation, sulfide concentration, etc.). Some of these differences are illustrated in the updated CSMs developed as part of this RI Report[249] and show how key physical and chemical parameters vary across habitats (e.g., marshes and waterways) and vertically within sediment in waterways and marshes, as described below.

High-resolution marsh cores provided a detailed characterization of the vertical pattern of methylation/demethylation dynamics that was used to generate a working hypothesis of the biogeochemical factors (e.g., anoxic conditions, AVS formation) that limit methyl mercury concentrations to levels comparable to sites with much lower total mercury (e.g., Krabbenhoft et al. 1999; Benoit et al. 2003). SSE and other testing show that a large proportion of mercury in sediment is bound in low-availability sulfide complexes, and only a small fraction (less than 4 percent) of the mercury is present in a form that is readily available for methylation. Further, the RI data show that the available fraction of mercury in sediment decreases from the lower reaches (where total mercury concentrations are lowest) to the upper reaches (where total mercury concentrations are highest). These findings are supported by other RI studies, which 1) provided additional site-specific data on the geochemical sequestration of COPCs in sediment and porewater, redox profiles, and organic matter dynamics; 2) expanded the analyses of COPCs in receptor tissue, toxicity, and bioaccumulation patterns in waterways and marshes; and 3) affirm the hypothesis that anoxic conditions in marsh and waterway sediments promote formation of stable mercury sulfide complexes that have limited bioavailability to methylating bacteria.

[249] Refer to Appendix H.

In addition to isolating the highest mercury concentrations in sediment, burial is also an important process influencing mercury methylation, as the bacterial methylation of inorganic mercury occurs primarily in the sulfate reducing zone in the top few centimeters in waterways and typically at a depth of more than 5 cm in the marshes. As a result, peak methylation in waterway sediment likely occurs near the surface and not at depths where mercury concentrations are highest. Although methyl mercury concentrations are typically higher in the marsh surface sediment than in the waterway surface sediment, peak methyl mercury concentrations in the marshes are typically at depth (10 to 20 cm) and largely isolated from ecological receptors. Although dissolved-phase methyl mercury can be elevated in marsh sediment porewater relative to the total concentrations in surface water, dissolved-phase transport of methyl mercury from the marshes through surface exchange and interflow drainage processes is low relative to the COPC transport from the waterway sediment bed via fluff layer interactions. Further, the mass of dissolved methyl mercury exported from the marshes was found to be 7 to 33 times less than the mass of particulate methyl mercury imported to the marshes due to particulate deposition and accumulation during tidal flooding. The result is that there is a net movement of methyl mercury into the marshes from the waterways.

For PCBs, the key physical process controlling bioavailability is burial and isolation from surface water. Adsorption of PCBs to the abundant fine POC in the BCSA combined with their low water solubility is a physical-chemical process that maintains low levels of dissolved PCBs in surface water. These physical and chemical processes are reflected in the high-resolution core data, which demonstrate the burial of PCBs in marshes over time, and by the low degree of biouptake.

8.1.6 Study Question 6 (Fate and Transport): Is there a potential for changes in the system (natural or anthropogenic) that could affect the type and distribution of stressors, especially chemical fate, transport, and bioavailability?

Natural and anthropogenic changes to the system will occur in the future. Depending on scale, scope, and timing of these changes, they could affect the fate, transport, and bioavailability of COPCs during the BCSA remedy. Natural changes include the response of the system to large storms (e.g., hurricanes) or sea level rise. Anthropogenic changes can include, but are not limited to, regional flood control with diking, pumping, tide gates, and storm tide gates; channel filling and straightening; armored crossings (i.e., bridge abutments); stormwater management, including routing and concentration of flow; sewage and combined sewer management on the Hackensack River; and upstream reservoir management for flows and sediment content. Within a 30-year planning horizon, there are no anticipated changes in the land use patterns of the watershed that would significantly change the system. Additionally, given the regulatory limits on development that might have an impact on the marshes, it is unlikely that any future human activities would be approved that will result in substantial alteration or destruction of the marshes.

Higher than normal tides and rainfall occurred during the RI and provide some indication of the resiliency of the BCSA to change. During the RI, the combination of Hurricane Irene and Tropical Storm Lee over a 10-day period was a large magnitude event with a return frequency estimated to be less than a once in 100 years event, and the flooding associated with the Hurricane Sandy storm surge was estimated to be less than once in a 500 years event. Despite these high intensity events (i.e., exceptionally high rainfall with simultaneous peak tides, record storm surge), the system remained largely unchanged. The banks along the stream channels and marshes were not observed to change or erode appreciably. Minor shifts in mudflat structure were observed only near concentrated upland flows into the tidal portion of the BCSA. Comparison of the waterway sediment bed elevation profile from the beginning of the project in 2008 to 2014 (post-Hurricanes Irene and Sandy) indicates net erosion of the sediment bed occurred in limited, localized areas (6 percent) of the waterway. The remainder of the waterway exhibited no change or some net accumulation of sediment, indicating a return to dynamic equilibrium conditions similar to conditions prior to the large storms. In the absence of any major changes to the system, sea level rise will maintain an environment favorable for continued sediment accumulation in the BCSA and further physical isolation of COPC residuals.

Hurricane Sandy caused major damage to infrastructure throughout the coastal areas in New Jersey and New York, although without much noticeable impact on the BCSA waterways and marshes. In response to those impacts, several studies were conducted on improving flood protection and coastal community resilience. Commissioned by Rebuild by Design (An Initiative of the President's Hurricane Sandy Rebuilding Taskforce), the "New Meadowlands" project report (Rebuild by Design 2014) put forth an integrated vision for protecting, connecting, and growing the Meadowlands as part of a larger regional analysis (metropolitan area of New York) that mapped a maximal spectrum of risks to a comprehensive set of vulnerabilities, combining flood risk with social vulnerability, vital network vulnerability, pollution risk, and other considerations. The authors note that wherever this risk profile is greatest, "federal investments in protection make most sense" and identified "the Meadowlands area as an urgent priority" (Rebuild by Design 2014). The report includes identification of three pilot study areas in the Meadowlands. Pilot Study Area 1 (Little Ferry, Moonachie, and Carlstadt) includes a large portion of the BCSA.

The development of the "New Meadowlands" concept plan led to $150 million of starter money going from the U.S. Department of Housing and Urban Development to NJDEP to plan, design and construct flood and storm surge protection measures and around Berry's Creek (HUD 2014). Such measures, if constructed, would likely alter the hydrodynamics and sediment transport and deposition dynamics in a large portion of the BCSA. To ensure the potential for adverse effects on the BCSA remedy are minimized, NJDEP, EPA, and the BCSA Group are meeting and exchanging information as the respective alternatives analyses go forward.

Other anthropogenic changes are not planned for the BCSA, except for periodic repairs and replacements of tide gates, in particular the PIC tide gate. Construction of the rail crossing over the northern portion of MBC has caused only localized effects on the sediment bed. West Riser and Rutherford tide gate replacements did not result in apparent changes in sediment bed or COPC distribution in those areas.

The detailed alternatives evaluation during the FS will take into account alterations of the system through the remedial actions, such as dredging, which could change the redox conditions in the BCSA sediments, or long-term improvements in overall regional water quality that alter dissolved oxygen in the BCSA.

8.1.7 Study Question 7 (Risk Assessment): What are the primary CERCLA-relevant COPCs that pose unacceptable risk? How does this risk compare to effects caused by other stressors in the system? How do these risks interact with effects caused by non-chemical stressors?

The baseline human health and ecological risks assessments are not yet complete and will be submitted before the final RI report. The risk analysis to date indicates that mercury, methyl mercury, and PCBs are the primary COPCs contributing to elevated risks in the BCSA. Overall, the calculated risks are highest in the upper reaches of the system and decrease in the lower reaches, consistent with the distribution of COPCs in sediment and surface water. Estimated potential risks in the lower reaches approach those calculated for the reference sites. This pattern is observed in both waterway and marshes, although the magnitude of the risks in the marshes is much lower than that in the waterways due both to an absence of exposure pathways (i.e., for human receptors) and much lower COPC levels in marsh detritus, which is the primary source of COPC contributing to ecological exposures in the marshes.

Stressors not related to the site also pose potential risks to human and ecological receptors. Regional sewage discharges, for example, pose health risks to recreational users. Waterborne pathogens in the BCSA typically exceed surface water standards and comparatively pose a greater risk of adverse health effects to recreational users of waterways than the site-related stressors.

For ecological receptors, low dissolved oxygen conditions created by regional sewage discharges and other effects from large-scale urbanization have been documented as important determinants of the regional ecology and are the dominating influences on the aquatic community composition in the BCSA. The fish and benthic communities in the BCSA are no different than those in the regional reference sites and do not vary in response to COPC levels. COPC-related effects can add to stresses on the aquatic community, but the RI data indicate that this incremental impact is small. There are, however, estimated incremental potential risks to the wildlife community from COPCs that have accumulated in fish and other aquatic organisms.

8.2 Study Questions Related to Remedy Evaluation

The following is a discussion of the study questions that relate to the evaluation of remedial alternatives for the BCSA. The discussion provided herein presents key considerations to these study questions based on the findings of the RI Report and risk assessments. These study questions will be more comprehensively discussed in the FS Report, once the remedial alternatives have been identified for the site.

8.2.1 Study Question 8 (Remedy Evaluation): What is the ranking of the stressors (legacy sediments, atmospheric deposition, storm water runoff, relative mass loading from distinct tributaries and Hackensack River tidal inputs) with regard to their importance to risk?

Waterway BAZ sediment in UBC and upper MBC (to the southern end of Walden Swamp) contributes mercury, methyl mercury, and PCBs to the food web and is the stressor source that contributes most importantly to COPC risks related to legacy sources in the BCSA. Birds foraging in the waterways and people who catch and consume fish are the receptors most exposed to the BCSA COPCs associated with the waterway BAZ sediment source.

Other ongoing sources of COPCs (e.g., atmospheric deposition, stormwater runoff) contribute to COPC loads in the BCSA, but are minor contributors of total COPC mass relative to UBC/MBC sediments under current conditions, though they could become important future sources in a post-remedial BCSA. For example, research in other systems indicates that atmospherically deposited mercury may be more readily methylated and bioaccumulated than mercury already present (Harris et al. 2007; Orihel et al. 2006, 2007, 2008) and, therefore, more important than suggested by a mass analysis alone. In addition, atmospheric deposition will continue to be a source of mercury and other COPCs to the system following remediation. For example, research on the Saint Lawrence River in Canada suggested that atmospheric deposition and tributaries represented more important ongoing inputs to mercury in fish than did legacy mercury in sediment (Hodson et al. 2014).

Sediment from the Hackensack River contributes COPCs to BAZ sediment. Under current conditions, Hackensack River sediments, which are cleaner than legacy contaminated sediment, contribute a proportionally small percentage of COPCs to the BAZ, and overall contribute to natural recovery in the system, especially in the lower reaches of the system which are subject to twice-daily exchanges with the Hackensack River. In the future, if the higher COPC levels in UBC and MBC sediments are remediated, COPC levels in Hackensack River sediment will be the predominant source of sediment-associated COPC loading to BAZ sediment.

Fish and other aquatic species are accumulating COPCs, but the available data indicate that site-related COPCs are not measurably affecting the composition of the aquatic community. Aquatic community composition in the BCSA is similar to the reference sites and there is no evidence of changes in biological community composition in response to COPC exposure or uptake.

8.2.2 Study Question 9 (Remedy Evaluation): What risk reduction is achievable in the BCSA, given regional background contamination, as well as existing non-CERCLA and non-BCSA stressors?

The collective analysis in the RI indicates the primary source of COPCs leading to uptake in biota, transport to marshes, and the overall driver of COPC risk are the COPCs associated with the fluff layer interacting with the very top layer of waterway sediment in the upper reaches of the system. Ultimately, then, the magnitude of risk reduction that is achievable in the BCSA is tied to reductions in COPC concentrations in this very top layer of waterway sediment.

Over the long term, the magnitude of risk reduction achievable will be dictated by regional conditions. COPC contribution from the upland portions of the BCSA watershed, from atmospheric deposition, and regionally from the Hackensack River will be ongoing sources of COPCs to waterway surface sediments. Though these sources cumulatively contribute minimally to COPC loads in the upper reaches of the system now, they will play an increasing role in defining achievable levels of COPCs in sediment as the BCSA recovers. Regional contributions from the Hackensack River already play an important role in defining COPC levels in the lower reaches of the system, where COPC concentrations are at or near those in reference sites. Given this influence, attempts to lower COPC concentrations in these areas would not achieve sustainable risk reductions due to recontamination from elsewhere in the region.

Further, the comprehensive impacts of regional urbanization on local ecology have an important influence on the composition and character of the aquatic community. Recovery in the aquatic community will similarly be tied to regional conditions. Improvements in dissolved oxygen levels, decreased nutrients, and other water quality changes can lead to regional recovery that also can occur in the BCSA.

As noted in EPA's Contaminated Sediment Remediation Guidance for Superfund Sites (USEPA 2005), remedial action objectives should target achieving meaningful risk reductions rather than attempting risk elimination. This is especially important at large urban sites, such as the BCSA, where a multitude of stressors is common. In addition, the current and future land use and water resources use for the BCSA watershed and lower Hackensack River watershed must be considered. Incorporating these various factors into remedial alternative identification, evaluation, and eventually selection will allow for adoption of remedial measures that can be feasibly implemented and that will have the greatest overall benefit.

8.2.3 Study Question 10 (Remedy Evaluation): What is the rate of natural recovery for chemical stressors, and what recovery is anticipated for non-chemical stressors in the absence of CERCLA-related remedial activity?

Natural recovery will be an important consideration in remedy design. In the BCSA, natural recovery is occurring via a variety of processes. These include physical processes such as sediment deposition that leads to COPC burial, chemical degradation or other transformation processes, reduction in bioavailability through sorption or other processes, and dispersion. The nature and magnitude of each of these factors will need to be considered during remedy selection and design.

Natural recovery can be evaluated using multiple lines of evidence, including sediment core data and surface concentration trends over time, long-term trends in surface water concentrations, and long-term trends in biota tissue concentrations (USEPA 2014). Delineation of sediment concentrations in areas of recurring resuspension and predictive numerical modeling are important elements to the evaluation of the rates of natural recovery.

The most definitive record of historical concentration decreases in the BCSA is documented by the high-resolution cores. With some exceptions and variations in waterways that can be explained, the pattern evident in the RI data, most notably the COPC concentration profiles in the high-resolution cores, is that the deeper sediments contain significantly higher concentrations of COPCs than shallow sediments. This demonstrates that more recent cleaner sediments are covering and burying the older sediments in both waterway and marsh habitats.

Analysis of concentrations trends in tissue and surface water from the past to present was constrained by the small number of historical samples in a limited number of locations, potential data quality issues, sampling method inconsistencies, and early analytical methods (which improved over time). These factors make it challenging to evaluate current RI data in the context of historical data from the BCSA to establish trends with confidence. However, taken as a whole, the comparison of RI data to historical data in surface water and surface sediment shows a decreasing trend over time. Data collected during the RI for site characterization and routine monitoring of surface water and fish tissue show a high degree of variability across seasons and years. There appears to have been a decrease in PCB concentrations in fish tissue, and, while methyl mercury concentrations in fish tissue from year to year are variable, the concentrations are generally stable overall. The collective data set has established a thorough characterization of baseline conditions and associated variability, and will be used to measure the effectiveness of remedial measures, especially if implemented in an adaptive management approach.

Regional condition recovery will also be an important consideration in the evaluation of remedial actions, as more than 70 percent of the inorganic sediment that deposits in the BCSA comes from the Hackensack River estuary (Graphic 3). Following remedial actions in areas of the BCSA where risks are elevated and greater than the regional condition, the new sediment deposited in these areas will have a strong regional signature. Recovery of non-chemical stressors (e.g., low dissolved oxygen) will also be a consideration in remedy design and monitoring of performance. More detailed evaluation of recovery rates will be included in the FS.

8.2.4 Study Question 11 (Remedy Evaluation): What are potential remedial measures to reduce CERCLA-relevant risk by 1) source control, 2) reducing exposure pathways, and 3) reducing bioavailability?

For all sediment sites, there are a few basic remedial approaches. Remedial measures potentially applicable to the BCSA include removal, cover, capping, options to accelerate natural recovery, and natural recovery. As is discussed in Sections 6.1 and 8.1.2, most primary sources have already been removed or substantially diminished through actions directed or monitored by the NJDEP and EPA. Resuspension of and particulate interactions with waterway surface sediment represents the principal ongoing source of COPCs to surface water and, in turn, the aquatic food web. In addition, through the transport of particulate COPCs exchanged from the surface of the waterway sediment bed to the water column, high concentration areas of the waterway sediment bed act as a secondary source of COPCs to downgradient areas of the waterway and to the adjacent marshes. Control of the exchange of COPCs from the waterway surface sediments would reduce the COPCs in the water column and transport of COPCs to the surface of the marshes, thereby reducing COPCs at key exposure points. Potential remedial alternatives evaluated in the FS will therefore focus, in part, on how best to minimize this secondary source and limit potential associated exposures.

Removal, capping, monitored natural recovery, enhanced monitored natural recovery, and thin layer placement are remedial approaches that have been evaluated for waterway sediments in the Development and Screening of Remedial Alternatives Memorandum (BCSA Group 2016) and will be evaluated further in the detailed alternatives analysis. Combinations of approaches will also be evaluated. It is anticipated that risk reduction in non-source areas can be achieved through thin layer placement (i.e., 2 to 6 in.) of clean sediment, possibly with amendments to reduce the bioavailability of COPCs. Pilot studies of the technologies have been undertaken at the site, and generally have shown positive results. Monitored natural recovery alone or in combination with other approaches such as capping or removal is a viable remedial technology for some reaches of the BCSA. The net depositional environment of the BCSA in the framework of increasing sea levels over the likely planning horizon (30 years) is conducive to monitored natural recovery as part of the remedy.

8.2.5 Study Question 12 (Remedy Evaluation): What net reductions in risk would be associated with alternative remedial measures (or combinations of these), in terms of both reducing the net risk levels and decreasing the time required to reach specified risk levels? How would these enhance the overall use (or value?) of the BCSA, consistent with long-term planning for the New Jersey Meadowlands?

Net risk reduction will be assessed while considering the impact of any remedy or combination of remedies in the FS. The FS will consider the chemical and physical risks associated with remedies in terms of the realities of the Meadowlands (e.g., urban setting, regional contamination, legacy contamination) and likely future flood control projects being evaluated by the NJDEP as part of the Rebuild by Design initiative.

The New Jersey Meadowlands Master Plan was last revised more than 10 years ago (2004) and is likely to be revised by the NJSEA (aka Meadowlands Regional Commission), following its merger with the former NJMC in 2014. In the current master plan, emphasis is placed on the value of the marshes and waterways in providing wildlife habitat and recreational opportunities. Further, although not discussed in the Master Plan, the marshes provide critical protection against incoming hurricane storm surges. The NJDEP regional fishing and crabbing prohibitions are also likely to continue well into the future.

Another important consideration is the risk of remedy itself and how that will affect the BCSA in the long term, for example the long-term stability of the marshes. Stakeholders and agencies with interests in the site include the NJSEA, NJDEP, USFWS, USACE, NOAA, local government entities and their residents, and non-governmental organizations (e.g., Hackensack Riverkeeper). Additional stakeholders are identified in EPA's Stakeholder Involvement Plan. Stakeholders will play a key role in assessing the value of various remedies for the site.

The importance of considering remedy implementation risks as part of short-term effectiveness is emphasized by EPA; in particular, the National Contingency Plan requires an assessment of the potential short-term risks created by implementing the remedy (USEPA 1990). Similarly, short-term impacts and effectiveness as well as long-term effectiveness and performance are part of the evaluation criteria for detailed analyses of alternatives, which will be conducted following completion of the RI, including the baseline risk assessments.

Given the potential uncertainties in future site conditions (e.g., sea level rise, dissolved oxygen levels, salinity, and flood control projects) and the expected reduction of COPC bioavailability following implementation of remedial actions, an adaptive management approach would likely be beneficial in optimizing the long-term net risk reduction within the BCSA. For example, remediation of secondary source areas in the waterways would reduce ongoing COPC transport and accumulation in the marshes, thereby increasing the rate of natural recovery of the marshes. An adaptive management approach would also include performance monitoring of the effectiveness of waterway remedial measures on the marshes, so that uncertainties may be reduced in the evaluation of a remedial alternatives for the marshes. Such an approach is consistent with the EPA's Sediment Remediation Guidance (USEPA 2005). Data collected during the RI are more than sufficient to support the evaluation of the initial remedial options. However, the scope and scale of subsequent remedial actions should be informed by the performance of the initial remedial actions given the complexity of the site, the likely long duration of remedial actions, and the potential for changes/responses in the system that cannot be anticipated at this time. Finally, it is important to continue to collect and consider physical setting information related to evaluation of potential remedies. The BCSA is a large geographic area of water channels and marshes with limited access. This will present material handling and transportation challenges to successfully implement dredging and/or capping to the extent they are found to be necessary.

SECTION 9

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